

# **Analyzing the Feeding Behaviour of MEX Extruder Heads**

Master's Degree

Aleksi Modebadze



Tomas Bata University in Zlín  
Faculty of Technology  
Department of Polymer Engineering

Academic year: 2024/2025

# ASSIGNMENT OF DIPLOMA THESIS

(project, art work, art performance)

Name and surname: **Aleksi Modebadze**  
Personal number: **T23444**  
Study programme: **N0722A130002 Polymer Engineering**  
Type of Study: **Full-time**  
Work topic: **Analyzing the Feeding Behaviour of MEX Extruder Heads**  
Work topic in English: **Analyzing the Feeding Behaviour of MEX Extruder Heads**

## Theses guidelines

In the proposed master thesis the typical feeding temperatures and velocity's are set in the force measurement device and the force is measured by a load cell in-between the extruder drive and the extruder die. The same settings are simulated in Ansys Polyflow to observe if a prediction can be made.

First the material parameter should be measured for the temperature dependent Polyflow simulations.

Two materials are proposed, one with a thermal conductivity of 0.2 (perhaps PLA, but should be defined at the beginning of the thesis) and one a feedstock with a thermal conductivity of 1 W/(m·K).

Form processing of diploma thesis: **printed/electronic**  
Language of elaboration: **English**

**Recommended resources:**

Ch. D. Han, Rheology and Processing of Polymeric Materials, Oxford, 2007  
Z. Tadmor, C. G. Gogos, Principles of Polymer Processing, Wiley, 2006

Supervisors of diploma thesis: **prof. Ing. Tomáš Sedláček, Ph.D.**  
Department of Polymer Engineering

Date of assignment of diploma thesis: **January 2, 2025**

Submission deadline of diploma thesis: **May 9, 2025**

**prof. Ing. Roman Čermák, Ph.D. m.p.**  
Dean

L.S.

**Ing. Jana Navrátilová, Ph.D. m.p.**  
Head of Department

In Zlín March 3, 2025

## MASTER'S THESIS AUTHOR'S DECLARATION

### I take cognizance of the fact that

- by submitting my Master's thesis, I give consent to the publication of my thesis in accordance with the Act No. 111/1998 Coll., as amended, regardless of the result of the thesis defence;
- the Master's thesis will be stored in electronic form in the university information system and will be available for consultation;
- one copy of the Master's thesis in hard copy form will be kept and stored by Tomas Bata University in Zlín;
- my Master's thesis is fully subject to the Act No. 121/2000 Coll. on Copyright, on Rights Related to Copyright and on Amendment to Certain Acts (Copyright Act), as amended, particularly to Section 35 Paragraph 3;
- according to Section 60 Paragraph 1 of the Copyright Act, Tomas Bata University in Zlín has the right to conclude a licence agreement on the utilization of a school work as is specified in Section 12 Paragraph 4 of the Copyright Act;
- according to Section 60 Paragraphs 2 and 3, I may utilize my school work – Master's thesis – or grant a licence to utilize it only with the prior written consent of Tomas Bata University in Zlín, which in such a case is entitled to require me to pay a reasonable contribution in order to cover the costs incurred by Tomas Bata University in Zlín for the preparation of the work (up to their full amount);
- if software provided by Tomas Bata University in Zlín or other entities was used for the preparation of the Master's thesis only for learning or research purposes (i.e. for non-commercial use), the conclusions of the Master's thesis cannot be used for commercial purposes;
- if the output of the Master's thesis is any type of software product, the source codes and/or files of which the project is comprised are also considered part of the thesis; failure to submit this part may result in a failure to defend the thesis.

### I declare that

- I have worked on my Master's thesis independently and properly cited the literature used; in case of publication of the conclusions, I shall be listed as co-author;
- the submitted hard copy version of the Master's thesis and the electronic version uploaded to the IS/STAG are identical in content.

In Zlín on .....

.....

author's signature

## ABSTRAKT

Tato práce se zaměřuje na analýzu podávací síly při aditivní výrobě na bázi vytlačování pomocí kombinace simulačních a experimentálních metod. V prostředí Ansys Polyflow byl vyvinut model metody konečných prvků pro simulaci nelineárního, neizotermického proudění tryskou E3D V6. Studie klade důraz na predikci podávací síly namísto chování taveniny, s cílem replikovat odpor vznikající během posuvu filamentu.

Byly zkoumány dva materiály: ABS a polymerní kompozit s obsahem 316L. Každý z materiálů byl charakterizován vlastním modelem viskozity závislým na smyku a teplotně závislými materiálovými vlastnostmi. Pro popis viskózního chování byl použit Crossův model a teplotní odezva byla modelována pomocí Arrheniova zákona. Simulace probíhaly při třech různých teplotách trysky za konstantní vstupní teploty.

Okrajové podmínky zahrnovaly dvě varianty: plnou adhezi stěny a teplotně závislý skluz. Podávací síla byla experimentálně měřena pomocí snímače síly integrovaného do upravené hlavy 3D tiskárny. Měření byla prováděna za odpovídajících teplotních a průtokových podmínek.

Výsledky ukazují, že podávací síla je ovlivněna teplotou, typem materiálu a charakterem okrajových podmínek na stěně. I když simulované hodnoty síly zcela neodpovídají experimentálním datům, vykazují podobné trendy a řády velikosti, což naznačuje, že model zachycuje klíčové vlivy. Tento přístup přispívá k dalšímu rozvoji simulačních nástrojů pro predikci odporu při vytlačování materiálu.

Klíčová slova: aditivní výroba, MEX extruze, podávací chování, ABS, 316L, simulace

## **ABSTRACT**

This thesis focuses on the analysis of feeding force in extrusion-based additive manufacturing using a combination of simulation and experimental methods. A finite element model was developed in Ansys Polyflow to simulate the non-Newtonian, non-isothermal flow through an E3D V6 nozzle. The study emphasizes force prediction rather than melt behavior, aiming to predict the resistance encountered during filament feeding and help to understand the feeding behavior. Two materials were investigated: ABS and a 316L-polymer composite. Each material was characterized by its own shear-dependent viscosity and temperature-dependent properties. The Cross model was used for viscosity, and an Arrhenius law described the thermal response. Simulations were performed at three different nozzle temperatures, using a defined inlet temperature. The simulation setup included two wall boundary conditions: full wall adhesion and a temperature-dependent slip. The simulations were carried out under the same temperature and flow rate conditions as the force measurements.

Feeding forces were measured experimentally using a force sensor integrated into a modified 3D printer head. Results show that feeding force is influenced by temperature, material type, and feeding velocity. While the simulated forces do not fully match the experimental values, the results show similar trends and magnitudes, indicating that the model captures the main influencing factors. This approach supports further development of simulation tools for estimating resistance during material extrusion.

**Keywords:** Additive manufacturing, MEX extrusion, Feeding behavior, ABS, 316L, Simulation.

## **ACKNOWLEDGEMENTS**

I would like to begin by expressing sincere appreciation to my supervisor, prof. Ing. Tomáš Sedláček, Ph.D., for his guidance and consistent support throughout this work. His feedback helped clarify ideas and maintain focus during each phase of the project.

I am grateful to Univ.-Prof. Dipl.-Ing. Dr. mont. Clemens Holzer for assigning this project and giving me the opportunity to work on a topic closely linked to practical research.

Special recognition goes to Dipl.-Ing. Stephan Schuschnigg, whose deep technical knowledge, continuous feedback, and dedication had a major impact on this thesis. From the early stages of planning to the final evaluation, he provided clear explanations, challenged my assumptions, and encouraged me to approach each problem with critical thinking. His mentorship helped me build a solid understanding of the experimental process, and his availability for discussion greatly accelerated my progress. Working under his guidance was a valuable learning experience, both professionally and personally.

I also acknowledge Dipl.-Ing. Philipp Beier for his support during the experimental work and contribution to key aspects of the project.

*“Those who can not remember the past are condemned to repeat it”  
George Santayana 1905.*

## Contents

|                                                                                |           |
|--------------------------------------------------------------------------------|-----------|
| <b>INTRODUCTION .....</b>                                                      | <b>11</b> |
| <b>THEORETICAL PART .....</b>                                                  | <b>13</b> |
| <b>1 MATERIAL EXTRUSION (MEX) IN ADDITIVE MANUFACTURING.....</b>               | <b>14</b> |
| <b>2 FEEDING BEHAVIOR AND EXTRUSION FORCE IN MEX .....</b>                     | <b>16</b> |
| <b>3 MATERIALS .....</b>                                                       | <b>19</b> |
| 3.1 ULTRAFUSE™ ABS FILAMENT .....                                              | 19        |
| 3.2 ULTRAFUSE™ 316L FILAMENT .....                                             | 21        |
| <b>4 EXPERIMENTAL APPROACH .....</b>                                           | <b>23</b> |
| 4.1 DSC .....                                                                  | 23        |
| 4.1.1 <i>Experimental Procedure for DSC Measurement</i> .....                  | 24        |
| 4.2 DENSITY .....                                                              | 25        |
| 4.2.1 <i>Experimental Procedure for pvT Measurement</i> .....                  | 26        |
| 4.3 THERMAL PROPERTIES .....                                                   | 27        |
| 4.3.1 <i>Experimental Procedure for Thermal Conductivity Measurement</i> ..... | 27        |
| 4.4 RHEOLOGICAL PROPERTIES .....                                               | 28        |
| 4.4.1 <i>Bagley Correction</i> .....                                           | 29        |
| 4.4.2 <i>Weissenberg-Rabinowitsch correction</i> .....                         | 30        |
| 4.4.3 <i>Power-law</i> .....                                                   | 31        |
| 4.4.4 <i>Cross model</i> .....                                                 | 32        |
| 4.4.5 <i>Arrhenius model</i> .....                                             | 32        |
| 4.4.6 <i>WLF</i> .....                                                         | 33        |
| 4.5 EXTRUSION FORCE MEASUREMENT METHODOLOGY .....                              | 34        |
| 4.6 EXTRUSION FORCE TESTING DEVICE .....                                       | 35        |
| <b>5 SIMULATION .....</b>                                                      | <b>37</b> |
| 5.1 NUMERICAL SIMULATIONS OF EXTRUSION PROCESS .....                           | 37        |
| 5.2 SIMULATION METHODOLOGY .....                                               | 37        |
| 5.3 GOVERNING EQUATIONS AND MATERIAL MODELS .....                              | 37        |
| 5.4 SIMULATION SET UP .....                                                    | 40        |
| 5.4.1 <i>Geometry</i> .....                                                    | 40        |
| 5.4.2 <i>Meshing</i> .....                                                     | 42        |
| 5.4.3 <i>Set up</i> .....                                                      | 43        |
| 5.4.4 <i>Slip model</i> .....                                                  | 43        |
| 5.4.5 <i>Boundary Conditions</i> .....                                         | 44        |
| <b>PRACTICAL PART .....</b>                                                    | <b>46</b> |
| <b>6 RESULTS .....</b>                                                         | <b>47</b> |
| 6.1 DSC .....                                                                  | 47        |
| 6.2 DENSITY .....                                                              | 47        |
| 6.3 THERMAL CONDUCTIVITY .....                                                 | 49        |
| 6.4 RHEOLOGICAL PROPERTIES .....                                               | 50        |
| 6.5 EXTRUSION FORCE MEASUREMENT IN MEX .....                                   | 53        |
| <b>7 NUMERICAL SIMULATIONS OF EXTRUSION PROCESS .....</b>                      | <b>55</b> |
| 7.1 SIMULATION WALL SLIPPING. ....                                             | 55        |
| 7.1.1 <i>Temperature</i> .....                                                 | 55        |
| 7.1.2 <i>Velocity</i> .....                                                    | 60        |
| 7.2 SIMULATION WALL ADHERING .....                                             | 63        |

|           |                                                             |           |
|-----------|-------------------------------------------------------------|-----------|
| 7.2.1     | <i>Temperature</i> .....                                    | 63        |
| 7.2.2     | <i>Velocity</i> .....                                       | 63        |
| <b>8</b>  | <b>SIMULATION–EXPERIMENT CORRELATION AND ANALYSIS .....</b> | <b>66</b> |
| 8.1       | WALL SLIP SET UP RESULT.....                                | 66        |
| 8.2       | WALL ADHESION SET UP RESULT.....                            | 67        |
| <b>9</b>  | <b>CONCLUSION.....</b>                                      | <b>68</b> |
| <b>10</b> | <b>REFERENCES.....</b>                                      | <b>69</b> |
|           | <b>LIST OF FIGURES .....</b>                                | <b>74</b> |
|           | <b>LIST OF TABLES .....</b>                                 | <b>76</b> |
|           | <b>LIST OF ABBREVIATIONS .....</b>                          | <b>77</b> |

## INTRODUCTION

The initial technique for fabricating a three-dimensional object incrementally through computer-aided design (CAD) was fast prototyping, which emerged in the 1980s for the production of models and prototype components. The primary advantage of Additive Manufacturing (AM) is its capability to produce virtually any conceivable shape, facilitated by the layer-by-layer fabrication process. Additive manufacturing technology is predominantly utilized for modeling, prototyping, and tooling using specialized machines or 3D printers [1]. By adding material layer by layer, additive manufacturing AM is able to manufacture items, in contrast to traditional manufacturing methods like casting, shaping, or welding, which require molds and frequently significant material removal and extensive post-processing. Through the utilization of this method, the requirement for further post-processing is reduced, while at the same time, the manufacture of intricate geometries is made possible with increased efficiency [2].

Moreover, additive manufacturing AM, often referred to as 3D printing, has seen substantial growth, offering various advanced options. One widely used AM technology is Fused Deposition Modeling™ (FDM™), a registered trademark of Stratasys Inc., utilizing heated thermoplastic filament extrusion. The generic, standardized term for this technique is Fused Filament Fabrication (FFF), which falls under the broader category of Material Extrusion (MEX) [1]. MEX describes additive manufacturing processes characterized by affordability, efficient material usage, and the capability to create sophisticated geometries with minimal waste [3].

One of many key aspects influencing 3D printing quality is the extrusion force, generated by the drive mechanism of the extrusion system as it propels the filament into the nozzle. This force is affected by the temperature, material viscosity, and extrusion velocity, all of which influence the uniformity and stability of the printed result. To guarantee superior print quality, these parameters must be meticulously examined, regulated, and empirically proven.

The purpose of this thesis was to examine the material extrusion MEX feeding behavior concerning the necessary force for filament feeding, since the extrusion force is crucial in determining production stability, efficiency, accuracy, and print quality. Understanding the link between extrusion force and filament velocity is essential for ensuring reliable performance in the production process.

Utilizing a computational fluid dynamic (CFD) simulation model in ANSYS Polyflow<sup>(TM)</sup> one of the most important investigations, that was conducted for this thesis. The process understanding will be improved through the simulation of the extrusion process with certain boundary conditions, as well as through the comparison of numerical predictions to experiments conducted in real life. The optimization of these simulation models will allow for improved control over the dynamics of the material flow, which will in turn make it possible to determine the ideal processing settings that will reduce the number of defects and improve print reliability.

Different materials exhibit unique viscosity and flow characteristics; therefore, this study focuses on two materials: Ultrafuse ABS [4] and Ultrafuse 316L [5]. The fact that these materials exhibit different rheological behavior and thermal conductivity will provide us with a far more comprehensive understanding of the behavior of extrusion. The properties of flowability are directly influenced by temperature and velocity, and it is essential to comprehend and take this into consideration.

## **THEORETICAL PART**

## 1 MATERIAL EXTRUSION (MEX) IN ADDITIVE MANUFACTURING

The Fused Deposition Modeling™ (FDM™) technique is one of the most well-known additive manufacturing processes. Stratasys was the company that initially registered the trademark for FDM. Material Extrusion (MEX) (the name according to standard ISO/ASTM 52900:2021), uses the same principle of FDM and is a frequently used additive manufacturing technology. In this method, a thermoplastic filament is constantly fed into a heated extrusion nozzle, where it is allowed to melt before being deposited onto a build platform or the previously deposited layer in a layer-by-layer fashion. It is possible to achieve exact layer stacking by moving the nozzle in relation to the build platform along the X-Y plane, while simultaneously adjusting the platform vertically in z direction after each layer has been produced. Due to the fact that MEX is utilized in desktop, industrial, and research-based 3D printing systems, it is considered to be one of the most accessible and versatile approaches of additive manufacturing [6].

Material Extrusion process is a flexible process for printing many materials, predominantly thermoplastic materials because these material can soften as they are heated and solidifies when cooled. Acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), high impact polystyrene (HIPS), thermoplastic polyurethane (TPU) and polyamides (PA), are commonly used thermoplastics. Ease of extrusion allows for the use of high performance polymers such as polyether ether ketone (PEEK) and polyetherimide (PEI) that are very strong, heat resistant polymers; hence have a lot of rugged uses in aerospace and medical. In addition to thermoplastics, MEX includes paste-like and composite materials, such as ceramic reinforced filaments, concrete, and metal polymer feedstock. Ultrafuse 316L, a filament made of metal particles within a POM based polymer binder system, facilitates the creation of metal components through successive debinding and sintering procedures, hence enhancing the capabilities of MEX for metal additive manufacturing applications [7].

### Extrusion of Material: A Step-by-Step Example

In the beginning of the procedure, the extruder pushes the filament into the nozzle (see Figure 1), where it melts and the nozzle will deposit material onto the build platform where it cools down and solidifies. This will result in the formation of the first layer, which will be determined by the cross-section design of the object.

On top of the layers that came before them, subsequent layers are deposited in accordance with the slicing pattern, that was previously established. As the material is extruded in its molten condition, it adheres to the previously placed layers. A proper adhesion between layers guarantees structural integrity and stability during the printing process [6].

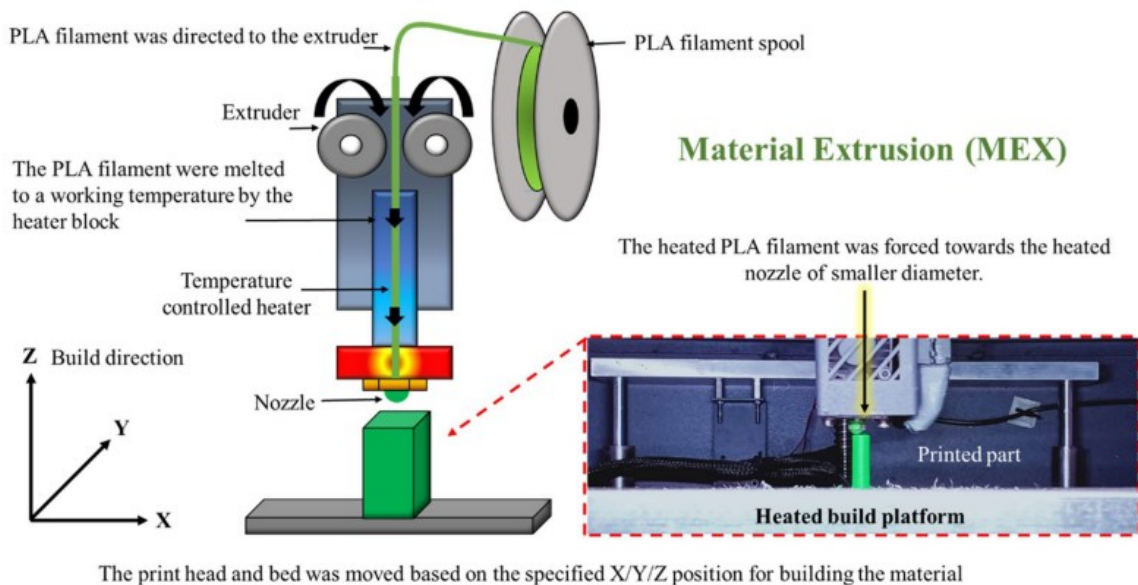


Figure 1 Outline of the MEX Process's [8]

A key challenge in this process is keeping the product functional, while reducing its weight and the amount of used material. This is an essential consideration in terms of manufacturing costs because both primary and support materials can be rather pricey. Companies are able to not only reduce their expenses, but also the environmental impact of their production processes by increasing the efficiency with which they use materials.

The shape of a product needs to be improved in order to successfully address these difficulties. It is possible to significantly reduce weight, while maintaining the same level of mechanical strength through the process of refining the structural design. Because it assists in the creation of complicated structures that are suitable for additive manufacturing, topology optimization is a strategy that is frequently utilized for this purpose. As a result of this strategy, components that are both lightweight and long-lasting are produced. This is because the material is only placed where it is required [8].

## 2 FEEDING BEHAVIOR AND EXTRUSION FORCE IN MEX

The filament feeding mechanism and the feeding forces during extrusion affect the efficiency and the quality of extrusion based manufacturing processes. Consistent material flow requires that the force on the material be applied controllably, avoiding under extrusion, clogging, or filament breakage [9]. The extrusion stability and print accuracy are dependent on the key parameters such as drive mechanism, extrusion speed, material viscosity and temperature [10].

It is proved from research that the temperature dependent viscosity has great influence on the bonding between layers and affects the mechanical performance and surface finish [11]. A motor driven feeding device is used to feed the filament into the extruder by a wheel that is in direct contact with the filament. It applies a feeding force to the filament as it spins at a set speed, moving the filament forward. However, these different resistive forces work in the opposite way and push this force back [12] therefore, it impacts how stable and even the extrusion process is [13]. Manufacturers can use these parameters to carefully tune MEX processes in order to increase the efficiency and reliability.

A slicer program is necessary to the MEX process because it takes geometry and process settings and creates printer commands from them. This software figures out the set of paths that must be taken to make the part, defining things like temperatures, layer height, production rate, and nozzle speed [12]. But one very important problem is designing and coordinating the orders that are sent to the extruder motor. To get good results, these directions need to be perfectly in sync with the machine's motion system, taking into account how the material flows and the pressure of extrusion. Any mismatch or delay between motion and extrusion can cause uneven material deposition, which can affect the accuracy of the print and the roughness on the surface [14]. Figure 2 presents an example of extrusion force behavior as a function of filament feed velocity at various extrusion temperatures. The graph illustrates a stepwise increase in extrusion force with increasing feed velocity, where two distinct linear regressions are identified. This is due to higher extrusion temperatures giving lower slopes, which indicate lower resistance with softening of the material.  $J_{\text{step}}$  is the step change in force which indicates the transition between two flow regimes to understand the material response at different process conditions [15].

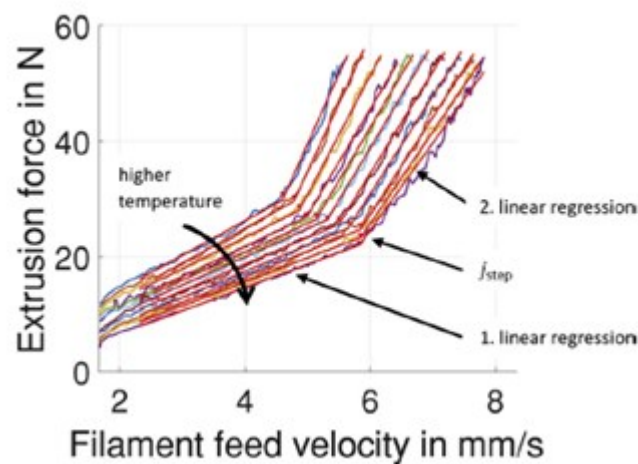


Figure 2 Extrusion force vs filament feed velocity at different temperatures [15]

The significance of temperature dependent viscosity in MEX, as well as the effect of temperature dependent viscosity on extrusion force, is emphasized in this analysis.

The possibility of filament buckling under excessive compression is a critical factor in the extrusion force measurement in MEX. The filament is driven into the heated liquefier via the feed pinch rollers and as the filament is compressed, the compressive stress increases. At high feed rates and/or high extrusion pressures, when the resistance at the liquefier entrance becomes significant, this buckling phenomenon can be particularly relevant due to the fact that compression above a critical threshold can trigger flow instability, irregular extrusion, and process failure [16].

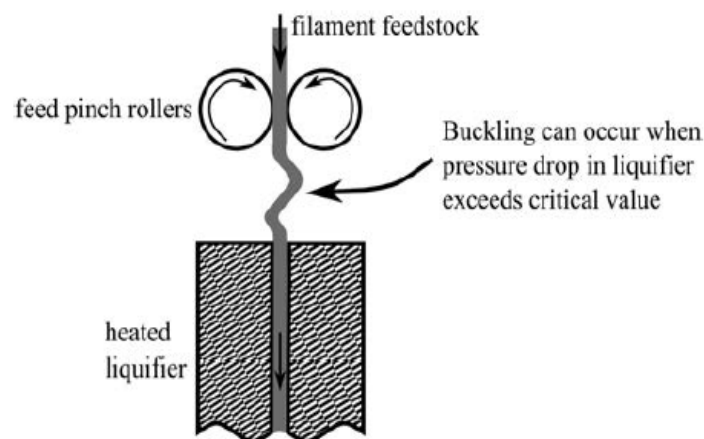


Figure 3 Filament buckling at liquefier entrance [16]

As illustrated in Figure 3, buckling occurs between the feed pinch rollers and the liquefier entrance, primarily due to the pressure drop inside the heated liquefier. Once this threshold is exceeded, the filament can no longer maintain its structural integrity, resulting in deformation, inconsistent material flow, and potential clogging [16].

Also, buckling at the liquefier entrance, filament deformation can occur within the PTFE tube under certain conditions. This phenomenon arises when the filament is constrained against the wall at multiple contact points due to insufficient clearance or misalignment. As the polymer softens during heating, compressive forces induced by feeding pressure can cause the filament to buckle into a serpentine shape along the tube wall—particularly at high feed rates or when the filament exhibits low mechanical stiffness. This form of buckling, typically associated with reduced tube diameters or poor alignment, is attributed to elastic instability under axial load and may develop independently of backflow effects.

While the referenced study employed a glass tube (see Figure 4) for in-situ visualization, the buckling mechanism is not exclusive to that material. Similar behavior is expected in PTFE tubes or any confined geometry where a clearance exists between the filament and the tube wall. In such cases, axial compression can trigger lateral instability, ultimately leading to buckling within the constrained channel [17].

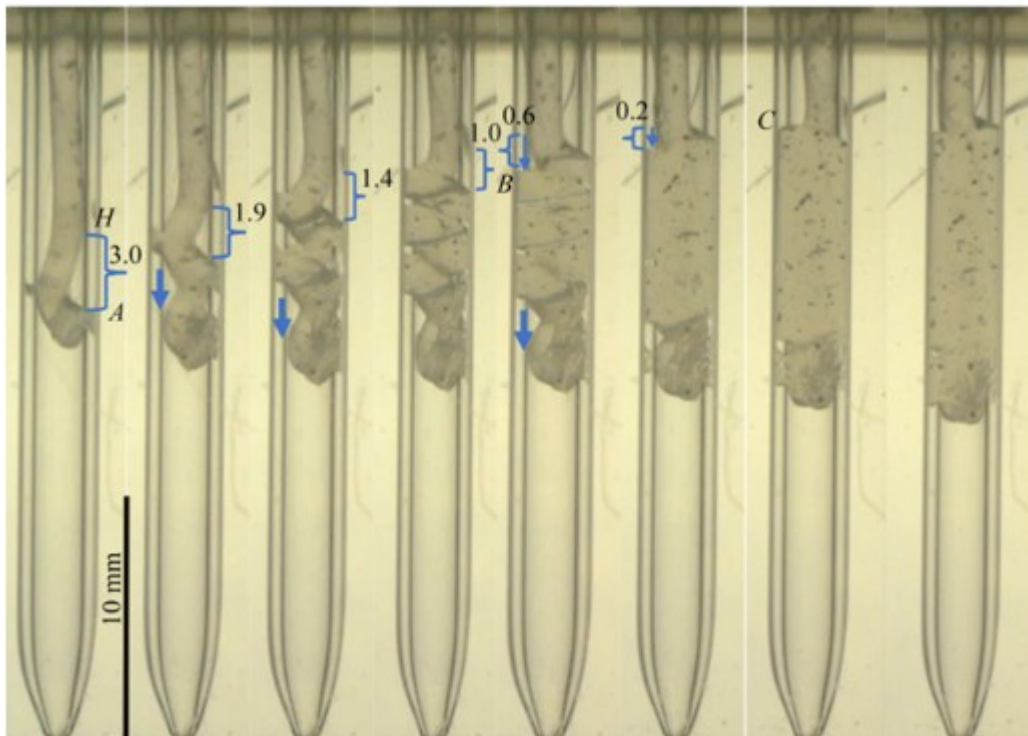


Figure 4 Visual sequence of filament buckling and gap filling within the observation tube [17]

### 3 MATERIALS

Two different materials were selected for the investigation, one ABS and a composite of polyoxymethylene (POM) and 316L steel powder. The biggest differences are in the viscosities and in the thermal conductivity, as the steel powder enhances it. Furthermore, these materials exhibit distinct structural characteristics: ABS is generally considered an amorphous polymer, while POM is semi-crystalline polymer.

Both materials were purchased from Montanuniversität Leoben, in the form of filament, to ensure a proper quality of the diameter and the ovality.

#### 3.1 Ultrafuse™ ABS filament

ABS, which stands for acrylonitrile-butadiene-styrene, is a material that is frequently used in the process of material extrusion additive manufacturing. It is highly regarded due to the fact that it possesses the ideal combination of mechanical strength, rheological behavior, and widespread availability [18]. ABS is a thermoplastic copolymer that is known for being able to change from a solid to a molten state many times without losing many of its qualities. The main components are acrylonitrile, styrene, and polybutadiene. In most cases, 20 % acrylonitrile, 25 % butadiene, and 55 % styrene make up the mixture. ABS has special properties because of these three parts working together (see Figure 5): acrylonitrile makes it more resistant to chemicals and heat, styrene makes it stiffer and easier to work with, and butadiene makes it tougher and stronger against impacts. By changing the amounts of these elements, you can also change the qualities of ABS, making it better for uses that need it to last longer, be resistant to heat, or absorb impacts [19].

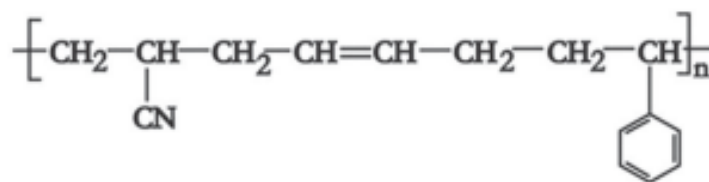


Figure 5 Chemical structure of ABS [20]

It is possible to produce ABS polymers by either mechanically blending the constituent components or by graft polymerization, which involves polymerizing styrene and acrylonitrile in the presence of a rubber component. Both of these methods are viable options for developing ABS polymers. Suspension polymerization, bulk polymerization, and emulsion polymerization are the three primary processes that are utilized in the production process. Among them, emulsion polymerization is the process that is utilized the most

frequently for the purpose of producing the grafted polybutadiene phase. This method guarantees the uniform dispersion of rubber particles inside the polymer matrix, hence boosting the material's toughness and resistance to impact [21].

Disadvantages of ABS include its limited suitability for outdoor use and low fire resistance. It degrades under prolonged exposure to UV radiation, leading to discoloration and loss of mechanical strength. This restricts its performance in environments with high sunlight exposure. ABS is also flammable. When exposed to high temperatures, it can melt, ignite, and emit harmful gases. Fire-resistant grades are available, but they require additional additives during formulation [22].

### Recommendations

| Property                       | Details for ABS                                           |
|--------------------------------|-----------------------------------------------------------|
| Drying Conditions              | 60 °C in a hot air dryer or vacuum oven for 4 to 16 hours |
| Support Material Compatibility | Single material breakaway                                 |

Table 1 Drying recommendations ABS filament [4]

### General properties

| Property         | Standard   | Average Value (ABS)    |
|------------------|------------|------------------------|
| Filament Density | ISO 1183-1 | 1037 kg/m <sup>3</sup> |

Table 2 General properties of ABS filament [4]

| Property                     | Standard | XY Direction | XZ Direction | ZX Direction |
|------------------------------|----------|--------------|--------------|--------------|
| Tensile Strength             | ISO 527  | 36.3 MPa     | -            | 21.3 MPa     |
| Elongation at Break          |          | 7.4 %        | -            |              |
| Young's Modulus              |          | 1958 MPa     | -            | 1608 MPa     |
| Flexural Strength            | ISO 178  | 56.6 MPa     | 58.3 MPa     | 38.6 MPa     |
| Flexural Modulus             |          | 1833 MPa     | 1767 MPa     | 1586 MPa     |
| Flexural Elongation at Break |          | 5.3 %        | 5.0 %        | 3.1 %        |

Table 3 Flexural and tensile properties of ABS filament [4]

In this section, an overview of Acrylonitrile Butadiene Styrene (ABS) key material properties (see Table 1, Table 2) and its recommendations (see Table 3) is presented, highlighting its mechanical, thermal, and rheological properties that make it a widely used material in MEX.

### 3.2 Ultrafuse™ 316L filament

Moving forward, the focus will shift to Ultrafuse™ 316L, a metal-polymer composite filament designed for metal additive manufacturing, consisting of polyoxymethylene (POM) and steel powder.

Ultrafuse 316L is a metal-polymer composite filament that was developed for MEX additive manufacturing by BASF. It makes it possible to manufacture components made of 316L stainless steel by utilizing ordinary Fused Filament Fabrication 3D printers. This filament is made up of a 90 % by weight of sinterable 316L steel powder and 10 % of binder polymers [23]. It is designed to be used for extrusion-based printing, and then it is subjected to debinding and sintering in order to produce a final product that is nearly all metallic [24].

| Type | Weight Green (g)  | Weight Sinter (g) | Weight loss (g) (%) | X Shrink (%)     | Y Shrink (%)     | Z Shrink (%)     |
|------|-------------------|-------------------|---------------------|------------------|------------------|------------------|
| A    | 274.69<br>(±4.95) | 243.24<br>(±4.30) | 31.45<br>(11.45%)   | 16.49            | 16.23            | 20.76            |
| B    | 276.40<br>(±1.44) | 244.99<br>(±1.29) | 31.41<br>(11.36%)   | 16.38            | 19.26            | 20.99            |
| C    | 277.18<br>(±0.47) | 245.70<br>(±0.42) | 31.48<br>(11.36%)   | 16.18            | 16.24            | 21.34            |
| D    | 276.82<br>(±0.23) | 245.31<br>(±0.22) | 31.51<br>(11.38%)   | 16.09            | 16.78            | 22.08            |
| Type | X Green (mm)      | X Sinter (mm)     | Y Green (mm)        | Y Sinter (mm)    | Z Green (mm)     | Z Sinter (mm)    |
| A    | 54.33<br>(±0.04)  | 45.37<br>(±0.09)  | 59.76<br>(±0.03)    | 50.06<br>(±0.08) | 62.44<br>(±0.97) | 49.48<br>(±0.89) |
| B    | 54.39<br>(±0.06)  | 45.48<br>(±0.02)  | 62.00<br>(±0.03)    | 50.06<br>(±0.02) | 62.90<br>(±0.14) | 49.70<br>(±0.10) |
| C    | 54.32<br>(±0.06)  | 45.53<br>(±0.04)  | 61.87<br>(±0.10)    | 51.82<br>(±0.02) | 62.98<br>(±0.07) | 49.54<br>(±0.13) |
| D    | 54.37<br>(±0.004) | 45.62<br>(±0.05)  | 64.31<br>(±0.02)    | 53.52<br>(±0.06) | 62.96<br>(±0.06) | 49.06<br>(±0.03) |

Table 4 Mass loss and dimensional shrinkage of all structure types after debinding and sintering [25].

During the debinding and sintering processes, each printed structure undergoes a reduction in mass and size. The Table 4 compares the average weight and dimensions of four different topologies (A–D) before (green) and after (sinter) the process.

Mechanical properties of sintered Ultrafuse 316L components are similar to that of traditionally made 316L stainless steel. Therefore, these parts qualify for use in the industrial, aerospace, and medical sectors where high corrosion resistance, mechanical strength, and thermal stability [26]. A dense metallic structure is obtained due to the post processing processes that are chemical or thermal debinding, followed by sintering at high temperatures and these processes remove the polymer binder completely [27].

When printing Ultrafuse 316L, it is necessary to do a very tedious parameter optimization. In this optimization, the extrusion temperature, print speed and drying conditions are included. This is done in order to make sure the layers bond properly and the dimensions are correct. In contrast to the MEX materials based on thermoplastics, metal polymer filaments require additional considerations like increased infill density and shrinkage compensation because of the material transformations during post processing [28].

## 4 EXPERIMENTAL APPROACH

This section is to give a brief description of some theory that is useful in the experiments..

### 4.1 DSC

Differential Scanning Calorimetry (DSC) is an analytical technique that allows for study of reactions of a material to heating or cooling. It is a method to determine the difference in heat flow between a test sample and a known reference while they are subjected to controlled temperature changes. The sample and the reference are placed in separate cells and both are heated or cooled at a constant rate and the difference between the energy input or release into the two is recorded. Applying specific calculations [29] to these measured differences help determine the thermal properties, such as heat capacity:

$$\frac{q/t}{\Delta T/t} = \frac{q}{\Delta T} = Cp \quad (1)$$

In equation 1: “ $q$ ” represents the heat energy in (J joules), “ $t$ ” the time in (s seconds) “ $\Delta T$ ” the temperature change in (K Kelvin) and “ $Cp$ ” is the heat capacity or energy required per unit temperature change (J/K)

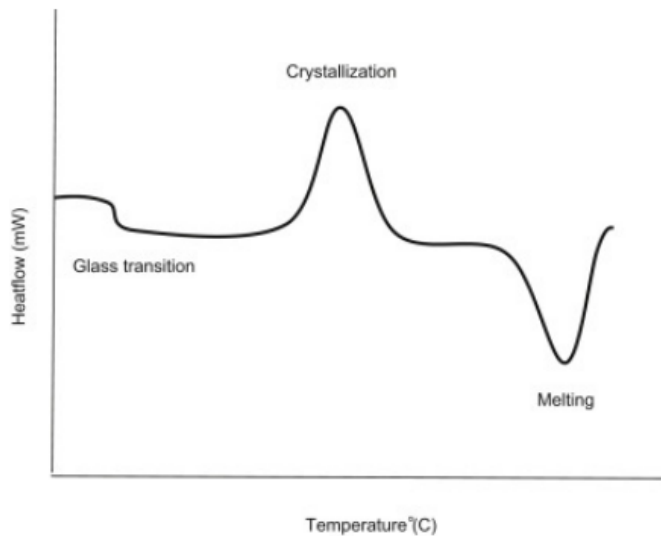


Figure 6 DSC curve illustrating thermal transitions [29]

Thermoplastics exhibit structural complexity due to their crystalline and amorphous regions. When heated, the amorphous portion undergoes a glass transition, shifting from a rigid, brittle state into a flexible, softened condition. This transformation occurs at a specific temperature called the glass transition temperature ( $T_g$ ). DSC thermograms detect this transition by capturing characteristic changes in heat flow, such as increased heat absorption

during melting or heat release during crystallization. Identifying these distinct thermal changes makes DSC an essential analytical tool for material characterization.

Figure 6 illustrates the thermal changes of a material during heating. The graph highlights critical processes such as the glass transition ( $T_g$ ), where the material transitions from a stiff to a more pliable state, crystallization, characterized by molecular organization, and melting, wherein the material transforms into a completely liquid phase.

#### 4.1.1 Experimental Procedure for DSC Measurement

Differential scanning calorimetry measurements were conducted using a Mettler Toledo DSC 3 (Mettler-Toledo, LLC, Switzerland) (see Figure 7) to analyze the temperature-dependent specific heat capacity of ABS and 316L samples. Three separate measurements were performed on ABS samples with masses ranging between approximately (6.84, 7.5 and 7.74 mg), as well as measurements on 316L (27.9, 28.11 and 25,16 mg). The measurement protocol involved an initial baseline calibration with two empty aluminum pans, followed by a calibration using sapphire to ensure accuracy. Subsequently, ABS and 316L samples were measured under identical experimental conditions.



Figure 7 Mettler Toledo DSC 1 STARe System

The heating cycle began at approximately room temperature ( $\sim 20\text{ }^{\circ}\text{C}$ ) and was increased up to around  $250\text{ }^{\circ}\text{C}$  at a controlled heating rate of  $10\text{ K/min}$ . After reaching the set maximum  $250\text{ }^{\circ}\text{C}$  temperature, an isothermal hold of 3 minutes was applied, followed by controlled cooling back to the starting temperature at the same rate. A second heating cycle was conducted under identical conditions. However, considering the relevance of processing

history on the thermal properties of materials, the specific heat capacity results are discussed in detail in the results section of this thesis and were obtained exclusively from the initial heating cycle.

## 4.2 Density

In additive manufacturing, especially in Material Extrusion processes, comprehending the pressure-volume-Temperature (pvT) connection is essential for precise density assessment of materials. Glass transition, melting, crystallization, and isotropization all cause substantial variations in the density and specific volume of polymers, which can all be investigated with dilatometric methods [30]. Building on this, pvT measurements serve as a fundamental tool for analyzing the thermodynamic behavior of plastics, elastomers, thermosets, and liquids, providing critical insights into their volumetric changes under different temperature and pressure conditions.

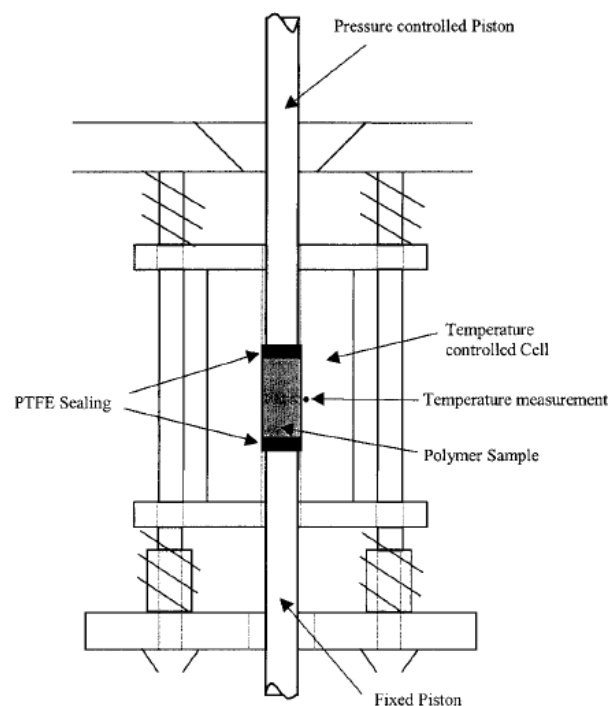


Figure 8 An illustration of a pvT cell [31]

The pvT measurement apparatus (Figure 8) comprises (pvT 100 SWO Polymertechnik Germany) a pressure-regulated piston, a stationary piston, and a temperature-regulated cell for accurate polymer analysis. The temperature is controlled by an electric heater band and air cooling, while a thermocouple monitors fluctuations. Spring-mounted cells facilitate movement, guaranteeing consistent pressure delivery, even when the sample adheres to the

walls. PTFE sealing ensures a consistent environment, inhibiting external interference. This configuration facilitates precise study of density and volume alterations, yielding critical insights into polymer behavior in MEX [31].

#### 4.2.1 Experimental Procedure for pvT Measurement

The pvT measurements were carried out in the GÖTTFERT RG 50 (Göttfert GmbH, in Zlin) system (see Figure 9). The tests were performed in the temperature range 80 °C to 260 °C at five different pressure levels approximately 70 bar to 390 bar. The thermal and compressibility behavior of both Ultrafuse 316L and Ultrafuse ABS samples is captured. The specific volume was recorded during isobaric testing at incremental temperatures. By observing material shrinkage, thermal expansion and possible phase transitions, this setup was possible. The data gathered are used as indispensable input for simulation models and give the details on how each material responds to the practical processing conditions in a thermal sense. See below table Table 5.

| Parameter                 | ABS   | 316L  | Unit |
|---------------------------|-------|-------|------|
| Test Temperature          | 265   | 265   | °C   |
| Material Weight           | 3.41  | 16.73 | g    |
| Force Transducer Capacity | 50000 | 50000 | N    |
| Capillary Length          | 25    | 25    | mm   |
| Capillary Diameter        | 2     | 2     | mm   |
| Piston Diameter           | 15    | 15    | mm   |

Table 5 Measurement parameters for ABS and 316L



Figure 9 Göttfert RG 50 system

### 4.3 Thermal Properties

Prior to MEX, there is some discussion of thermal properties such as DSC and pvT analysis. Now we are looking at thermal conductivity, one of the most important parameters which determine heat transfer, cooling rates, as well as the printed component quality.

Thermal conductivity is a material's ability to transfer heat and is a fundamental property. Conductors are materials with high thermal conductivity, insulators are materials with low thermal conductivity, and they are used to facilitate or restrict heat flow respectively. Solid conductors that are metals have typically thermal conductivity values of 10 to 400 W/(m·K), and insulating materials such as polymers, glasses, and ceramics usually are in the range 0.1 to 2 W/(m·K) [32]. Thermal conductivity is highly dependent on material composition, structure, and processing conditions. For instance, the presence of fillers or reinforcements in polymer composites can enhance thermal conductivity [33]. Since ABS and 316L are the primary materials in this study, evaluating their thermal conductivity is crucial as it directly impacts heat transfer, processing behavior, and final part quality. ABS is an amorphous thermoplastic with no sharp melting point but gradually softens over a temperature range [34] and naturally exhibits low thermal conductivity around 0.14 W/(m·K) [35], which affects its heat dissipation during processing and can lead to challenges such as uneven cooling, residual stresses, and warping in additive manufacturing applications. 316L is an austenitic stainless steel known for its corrosion resistance, good mechanical properties, and moderate thermal conductivity [36]. Ultrafuse 316L, a metal-polymer composite filament used in MEX additive manufacturing, the thermal conductivity behavior differs before and after the debinding and sintering process [28]. These measurements will be presented and analyzed in the practical section, providing insight into how processing parameters influence the final thermal properties of the sintered parts.

#### 4.3.1 Experimental Procedure for Thermal Conductivity Measurement

Thermal conductivity measurements of ABS and 316L samples were performed using a transient measurement approach with the GÖTTFERT RG 50 device, previously used for pvT measurements. Each sample was subjected to a controlled heat input, while temperature changes over time were continuously recorded. The measurement setup included a predefined power supply and precise temperature sensors to monitor the temperature increase and ensure data accuracy. Thermal conductivity was calculated by analyzing the transient temperature response during a controlled heating period, applying standard heat-

transfer equations. Table 6 provides the boundary conditions used for the thermal conductivity tests of ABS and 316L materials. Detailed results and discussions of the thermal conductivity measurements are presented in the results section of this thesis.

| Material | Voltage (V) | Target Temp. (°C) | Initial Temp. (°C) | Final Temp. (°C) | Duration (s) | Thermal Conductivity (W/m·K) |
|----------|-------------|-------------------|--------------------|------------------|--------------|------------------------------|
| ABS      | 24          | 210               | 213.7              | 216.3            | 120          | 0.198                        |
| ABS      | 24          | 230               | 234.3              | 236.9            | 120          | 0.195                        |
| ABS      | 24          | 250               | 254.7              | 257.2            | 120          | 0.195                        |
| 316L     | 69          | 210               | 224.5              | 227.3            | 120          | 1.489                        |
| 316L     | 69          | 230               | 245.2              | 248.2            | 120          | 1.369                        |
| 316L     | 69          | 250               | 263.3              | 266.4            | 120          | 1.332                        |

Table 6 Thermal conductivity measurement parameters for ABS and 316L

#### 4.4 Rheological Properties

No individual is truly an absolute novice about rheology, as the flow characteristics of liquids significantly influence our daily lives, whether intentionally or inadvertently [37]. Viscosity is a fundamental property that describes a fluid’s resistance to flow. It plays a crucial role in material extrusion-based additive manufacturing, as it influences material flow, layer adhesion, and overall print quality. The viscosity of a material determines how it behaves under shear forces, which is particularly important in extrusion processes where materials are pushed through a nozzle. Figure 10 represents how fluids can be broadly classified into Newtonian and non-Newtonian fluids based on their viscosity behavior under applied stress.

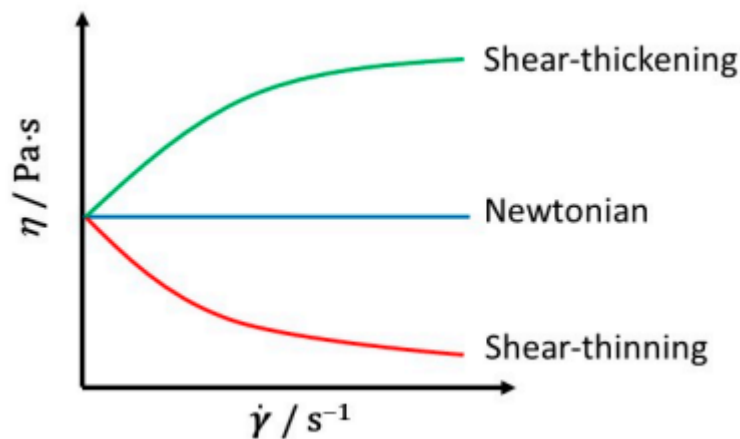


Figure 10 Viscosity behavior of Newtonian and Non-Newtonian fluids [38]

### Newtonian vs Non-Newtonian Fluids [38]

Newtonian fluids: These fluids exhibit a constant viscosity, meaning their flow behavior remains unchanged regardless of the applied shear rate. Examples include water, most gases, and simple liquids like honey or oil at stable temperatures. Their viscosity depends mainly on temperature and pressure, rather than shear rate [39].

Non-Newtonian fluids: Unlike Newtonian fluids, non-Newtonian fluids experience changes in viscosity when subjected to different shear rates. These materials can be further classified into:

- Shear-thinning (thixotropic) fluids: Viscosity decreases as shear rate increases (e.g., polymer melts, paints, and ketchup) [40].
- Shear-thickening (dilatant) fluids: Viscosity increases with shear rate (e.g., cornstarch-water mixtures, some suspensions) [41].
- Bingham plastics: These materials behave as solids under low shear but flow like a fluid once a yield stress is exceeded (e.g., toothpaste, chocolate, mud).
- Herschel-Bulkley fluids: A more general case of Bingham plastics, where both shear-thinning and yield stress characteristics are present (e.g., some industrial slurries) [42].

In the context of MEX, most thermoplastic polymers and composite filaments exhibit non-Newtonian shear-thinning behavior.

#### 4.4.1 Bagley Correction

When using a high-pressure capillary rheometer, the material flows from a large barrel (usually about 15 mm in diameter) into a much smaller die (around 1 mm in diameter) (Figure 11). As the material enters this narrow die, the pressure is measured right at the entrance. But this pressure is not just from the resistance of the material flowing through the die it also includes the pressure needed to speed up the flow as it goes from the slower-moving barrel into the faster-moving capillary.

This sudden increase in flow speed causes extra pressure changes that are captured in the measurement. So, the total pressure-drop that gets recorded is made up of three parts:

- Pressure-drop at the die entrance,
- Pressure-drop from shearing through the die,

- Pressure at the die exit.

Together, these give a pressure reading that is higher than the actual pressure drop across just the die itself.

To get the real wall shear stress which is needed for calculating the true shear viscosity you have to remove the effects of the entrance and exit pressure losses. This correction is called the Bagley correction [43].

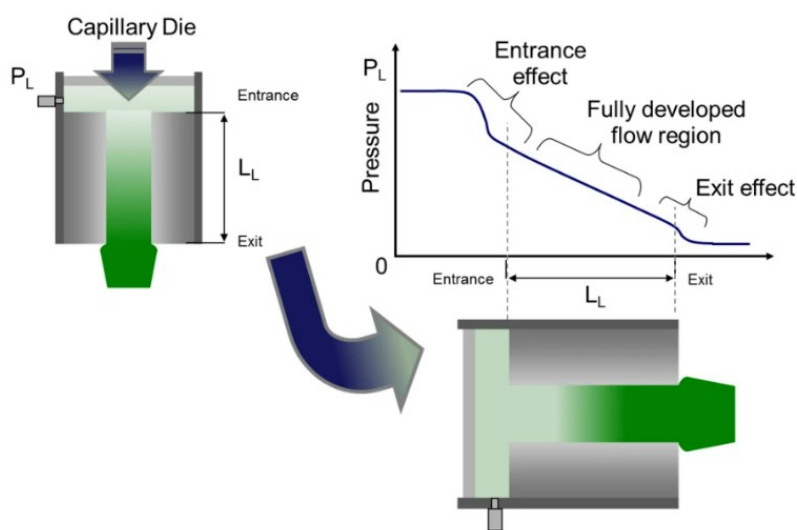


Figure 11 Bagley correction [43]

#### 4.4.2 Weissenberg-Rabinowitsch correction

Standard shear rate calculations are originally derived based on Newtonian fluid behavior, where the velocity profile in pressure-driven capillary flow is assumed to be parabolic and uniform. However, this assumption does not hold for non-Newtonian materials.

The Weissenberg-Rabinowitsch correction is applied in capillary rheometry to obtain a more accurate shear rate for non-Newtonian fluids. Standard shear rate calculations are originally derived based on Newtonian fluid behavior, where the velocity profile in pressure-driven capillary flow is assumed to be parabolic and uniform. However, this assumption does not hold for non-Newtonian materials.

In materials exhibiting shear-thinning behavior, such as polymer melts, viscosity decreases as shear rate increases, leading to an altered flow profile that deviates from the expected parabolic shape. This means that the shear rate at the capillary wall is typically higher than what the standard equation predicts, potentially leading to inaccurate viscosity measurements.

To correct for this effect, the Weissenberg-Rabinowitsch correction adjusts the calculated shear rate by accounting for the actual velocity distribution in the capillary. This ensures a more precise representation of the material's true flow behavior, making it essential for accurately determining viscosity in non-Newtonian fluids [44].

$$\dot{\gamma} = \frac{3n+1}{4n} \dot{\gamma}_a \quad (2)$$

In equation 2:  $n$  equals the slope of the logarithmic true shear stress vs logarithmic apparent shear rate curve at the apparent shear rate being corrected;  $\dot{\gamma}$  =true shear rate,  $\dot{\gamma}_a$ = apparent shear rate.

#### 4.4.3 Power-law

While the power-law model accurately depicts the behavior of certain fluids within a certain shear rate range, most non-Newtonian fluids exhibit more intricate flow properties. Consequently, they are more precisely characterized by alternate models, such as the Cross model, which encompasses a broader spectrum of rheological phenomena [45].

$$\eta = K\dot{\gamma}^{(n-1)} \quad (3)$$

In equation 3: „ $\eta$ “ is the viscosity (Pa·s), „ $K$ “ is the consistency index (Pa·s <sup>$n$</sup> ), „ $\dot{\gamma}$ “ is the shear rate (s<sup>-1</sup>) and „ $n$ “ is the flow behavior index.

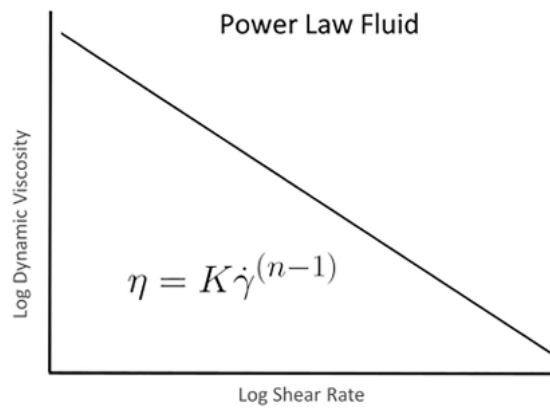


Figure 12 Power-Law Model [45]

The power-law is frequently employed due to its inherent mathematical simplicity and describes the structural viscous and dilatant material behavior (Figure 12).

#### 4.4.4 Cross model

The Cross model describes a viscosity dependency where at low and as seen in Figure 13 at high shear rates it behaves like a Newtonian fluid, but in-between like a power law material [46].

$$\eta = \frac{\eta_0}{1+(\lambda\dot{\gamma})^m} \quad (4)$$

In equation 4:  $\eta_0$ = zero-shear viscosity  $\lambda$ = Natural time (that is, inverse of the shear rate at which the fluid changes from Newtonian to power-law behavior),  $m$ = Cross model Index (= 1-n for large shear rates).

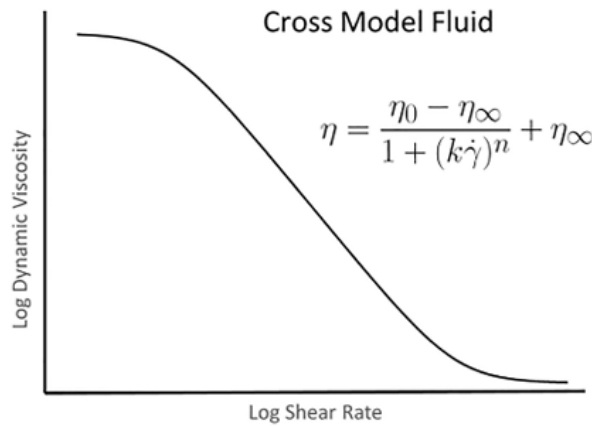


Figure 13 Cross model [45]

Figure 13 shows the viscosity shear rate relationship of a Cross model fluid. The curve represents how the dynamic viscosity decreases with increasing shear rate, illustrating shear-thinning behavior.

#### 4.4.5 Arrhenius model

The Arrhenius model is given as

$$H(T) = \exp \left[ a \left( \frac{1}{T-T_0} - \frac{1}{T_a-T_0} \right) \right] \quad (5)$$

In equation 5:  $\alpha$  = represents the ratio of activation energy to the thermodynamic constant.  $T_a$  is the reference temperature at which  $H(T) = 1$ . By default, the temperature shift  $T_0$  is set to zero, corresponding to the lowest thermodynamically permissible temperature. As a result,  $T$ ,  $T_0$ , and  $T_a$  are all considered absolute temperatures. However, they can also be expressed relative to a non-absolute temperature scale, in which case  $T_0$  represents absolute zero within that specific scale [46].

#### 4.4.6 WLF

The Williams-Landel-Ferry (WLF) equation is utilized to elucidate the temperature dependence of viscosity in polymer systems [47].

$$\log \frac{\eta}{\eta_g} = \frac{C_1 \cdot (T - T_g)}{C_2 \cdot (T - T_g)} \quad (6)$$

In equation 6:  $\eta$  and  $\eta_g$  represent the viscosity and the reference viscosity at the glass transition temperature, both expressed in (Pa·s).  $T$  and  $T_g$  denote the temperature and glass transition temperature, respectively, given in kelvin (K). The constants  $C_1$  and  $C_2$  are empirical, where  $C_1$  is dimensionless, and  $C_2$  has the unit of temperature (K).

Viscosity curves, depicting the correlation between temperature and the viscosity of solutions at their freezing or melting points, were obtained by extrapolating viscosity predictions from the glass transition temperature to the melting temperature.

#### Experimental Procedure for Viscosity Measurement

Viscosity measurements were conducted using a High-Pressure Capillary Rheometer (HPCR) Rheograph 25 and GÖTTFERT RG 50, manufactured by Göttfert Werkstoff-Prüfmaschinen GmbH, Germany. These viscosity tests were carried out at two institutions: Tomas Bata University in Zlín and Montanuniversität Leoben. For ABS, three repetitions were performed at each temperature to ensure consistent and reproducible results. On the other hand, the 316L data was repeated several times because of higher variability in the data and the need to get a sufficient amount of reliable data for analysis. Tests were performed (see also Table 7) on capillaries with 1.0 mm diameter and 20 mm length, at 210 °C, 230 °C and 250 °C in the presence of Ultrafuse ABS and Ultrafuse 316L materials. Applying the Bagley and Weissenberg-Rabinowitsch corrections to calculate the true shear rates and viscosities, pressure data and resultant forces were systematically recorded. The parameters used to calculate viscosity for Ultrafuse ABS and Ultrafuse 316L at its respective temperatures are given in Table 7.

| Parameters                | Value                          | Unit |
|---------------------------|--------------------------------|------|
| Shear rate                | 35–2000 (for all temperatures) | 1/s  |
| Temperatures              | 210, 230, 250                  | °C   |
| Diameter of the capillary | 1.0                            | mm   |

|                         |           |     |
|-------------------------|-----------|-----|
| Length of the capillary | 20.0; 0.2 | mm  |
| Pressure transducer 1   | 500       | bar |
| Pressure transducer 2   | 200       | bar |
| Piston diameter         | 15.0      | mm  |

Table 7 Parameters for viscosity measurement of Ultrafuse ABS and Ultrafuse 316L

## 4.5 Extrusion Force Measurement Methodology

The force measurement experiments performed for analyzing the feeding behavior of Ultrafuse ABS and Ultrafuse 316L during MEX process are described in this section. To investigate the effect of temperature and extrusion speed on the feeding force, experiment was conducted using a controlled variable approach. The extrusion speed was varied till the processing limit was reached while keeping the die diameter constant at 0.6 mm. After collecting the force data for different velocities, the temperature was changed and the process was repeated. Material behavior is significantly temperature dependent therefore these experiments were conducted from 230 °C to 270 °C for Ultrafuse ABS and Ultrafuse 316L.

### Custom Software for Extrusion Force Measurement

To control and monitor extrusion force measurement process, a software was developed in Python (see Figure 14). It is a program that displays real time values of temperature, force and speed, and it lets users set target temperatures, set extrusion speed and choose extrusion lengths. The features also include the ability to tar the load cell and view the measurement data, assuring precise and efficient data collection.

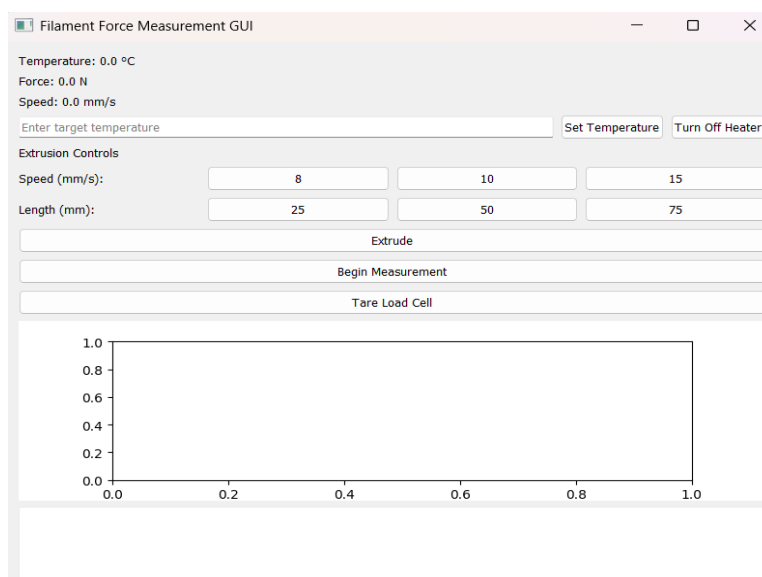


Figure 14 Filament force measurement developed for extrusion setup

The extrusion force was recorded for each material at different extrusion speeds, as they respond differently to changes in temperature and speed. In the following Table 8 are listed the details of the parameters used in the experiments.

| Material          | Temperature<br>°C | Feed rate (mm/s) |   |   |   |    |    | Length (mm)         |
|-------------------|-------------------|------------------|---|---|---|----|----|---------------------|
| Ultrafuse<br>ABS  | 230               | 2                | 4 | 6 | 8 |    |    | 200 300 400 500     |
|                   | 250               |                  | 4 | 6 | 8 | 10 |    | 200 300 400 500     |
|                   | 270               |                  | 4 | 6 | 8 | 10 | 12 | 100 200 300 400 500 |
| Ultrafuse<br>316L | 230               | 2                | 4 | 6 | 8 | 10 | 12 | 100 200 300 400 500 |
|                   | 250               | 2                | 4 | 6 | 8 | 10 | 12 | 100 200 300 400 500 |
|                   | 270               | 2                | 4 | 6 | 8 | 10 | 12 | 100 200 300 400 500 |

Table 8 Extrusion test parameters

#### 4.6 Extrusion Force Testing Device

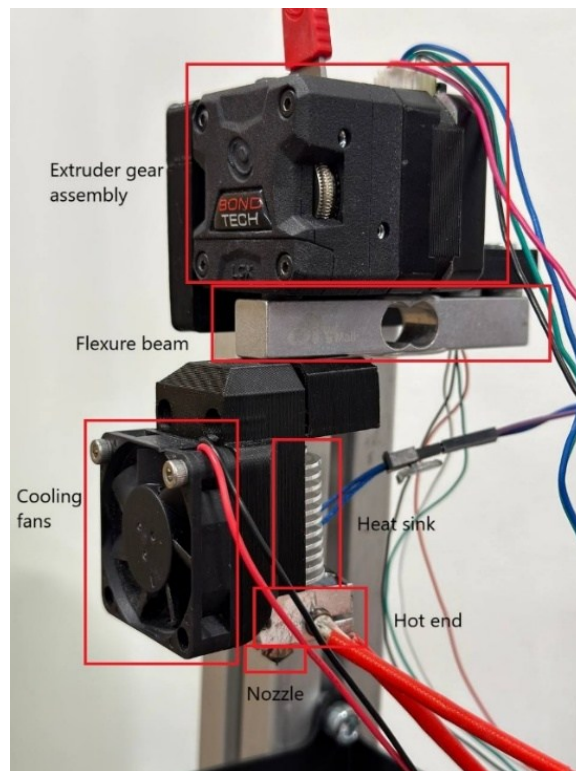


Figure 15 Extrusion force test set-up

A specialized experimental setup to measure the applied force by extruder on the filament was developed (see Figure 15). The feeding mechanism used was a Bondtech extruder with an E3D V6 hot end, which kept the filament transport stable. A load cell sensor was placed

between the feeding system and the extrusion head, in order to accurately record the extrusion force. By setting this up, we were able to monitor in real time the force variations of the extrusion process, which is the most crucial part of the whole feeding behavior, and obtain important information on the extrusion behavior under various conditions.

To determine in which ranges each material could be used, extrusion force measurements were made over a broad range of feed rates. The measurements were repeated five times at each temperature to ensure repeatability and to capture any variability of the extrusion behavior. The highest applicable extrusion force before failure was tested for both materials where the full range from minimal to maximum feasible speeds was tested. After this limit, the filaments could not pass through the extrusion head and had to be manually removed due to blockage. The maximum extrusion capacity of the system was defined using these observations. The performance and force response of each material is detailed in the results section and compared.

## **5 SIMULATION**

### **5.1 Numerical Simulations of Extrusion Process**

AM has been shown to be an effective and cost efficient means of production with a high quality output. Numerical simulation is a valuable tool to improve the product quality, optimize the life cycle and minimize the production costs. Over time, researchers are actively studying numerous techniques, methods, and modeling approaches that can reduce the labor intensity of AM process simulation [48]. High fidelity methods of material flow and phase changes using fundamental physics based equations have been observed as numerical methods that are being developed that arises from material flow and phase changes in additive manufacturing process. By means of these methods, these detailed process dynamics can be examined to help determine the relationship between extrusion parameters and the resulting bead cross-sectional geometries. Unlike numerical simulations which are computationally expensive, they are very useful in predicting material behavior, flow condition optimization, as well as enhancement of entire process stability. Thus, these advanced modeling techniques have been increasingly integrated into the AM research and development to increase the simulation accuracy and process efficiency [49].

### **5.2 Simulation Methodology**

These approaches are all widely used: Finite Element Method (FEM), Computational Fluid Dynamics (CFD), and Mesh Free methods. These methodologies offer different advantages for a particular simulation and are chosen for a given simulation. In a conventional FEM approach, basis functions are constructed within each finite element within Lagrange polynomials which are defined at Lagrange nodes. These nodes are then degrees of freedom, and therefore have physical significance in the computational model. This formulation guarantees that the solution is interpolated properly across the elements hence, increasing the reliability of numerical predictions made with MEX simulations [50].

### **5.3 Governing Equations and Material Models**

Numerical simulations of the extrusion process in Material Extrusion additive manufacturing rely on fundamental fluid flow and heat transfer equations to accurately predict material behavior, temperature distribution, and extrusion force. The governing equations include the continuity equation, Navier-Stokes equations, and the energy equation, which together

describe the motion and thermal response of materials during extrusion. Additionally, appropriate rheological models are required to capture the non-Newtonian behavior of polymer melts and metal-polymer composites like ABS and Ultrafuse 316L.

- The continuity equation ensures mass conservation in a flow system and is given by Equation 7:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \quad (7)$$

Where:  $\rho$  = density (kg/m<sup>3</sup>),  $v$  = velocity field (m/s) and  $t$  = time (s)

- Navier-Stokes Equations (Momentum Conservation) is given by Equation 8:

$$\rho \left( \frac{\partial v}{\partial t} + v \cdot \nabla v \right) = -\nabla p + \nabla \cdot (\eta \nabla v) + F \quad (8)$$

Where:  $p$  = pressure (Pa),  $\eta$  = dynamic viscosity (Pa·s),  $F$  = external forces

- Generalized Newtonian Fluid Model is given by Equation 9:

$$\tau = \eta(\dot{\gamma})\dot{\gamma} \quad (9)$$

Where:  $\tau$  = shear stress (Pa),  $\dot{\gamma}$  = shear rate (s<sup>-1</sup>),  $\eta(\dot{\gamma})$  = shear-dependent viscosity (Pa·s)

- Cross Model for polymer melts is given by Equation 10:

$$\eta = \eta_{\infty} + \frac{\eta_0 - \eta_{\infty}}{1 + (\lambda \dot{\gamma})^m} \quad (10)$$

Where:  $\eta_0$  = zero shear viscosity (Pa·s),  $\eta_{\infty}$  = infinite shear viscosity (Pa·s),  $\lambda$  = time constant (s),  $m$  = shear thinning exponent

- Carreau-Yasuda Model for polymer composites is given by Equation 11:

$$\eta = \eta_{\infty} + (\eta_0 - \eta_{\infty})[1 + (\lambda \dot{\gamma})^a]^{(n-1)/a} \quad (11)$$

Where:  $a$  = dimensionless fitting parameter controlling the transition for Newtonian plateau to the power law regions,  $n$  = power-law index.

Integrating these rheological models into FEM-based CFD simulations enables a more precise representation of material flow dynamics, shear stress distribution, and extrusion force behavior. This enhances the simulation's predictive accuracy, providing valuable insights into process parameters and their impact on extrusion stability, print quality, and overall efficiency in MEX [51].

## Geometry and Computational Domain

In extrusion-based additive manufacturing, nozzle geometry directly affects material flow, pressure distribution, and strand quality. Well-designed nozzles reduce pressure loss, promote uniform flow, and minimize shear stress near the walls. Modifying nozzle contours can improve velocity profiles and lead to more consistent extrusion performance. Computational Fluid Dynamics (CFD) simulations in this study demonstrate that gradual nozzle tapers result in smoother filament extrusion, minimizing turbulence and reducing flow resistance [52]. Similarly, research on strand cross-section formation reveals that nozzle geometry directly influences the shape and surface quality of extruded material. Nozzles with varying exit angles and diameters alter flow uniformity, impacting the strand width and thickness after deposition. The study highlights that sharp nozzle transitions can induce irregular flow, whereas optimized geometries promote uniform filament deposition and improved layer bonding [53].

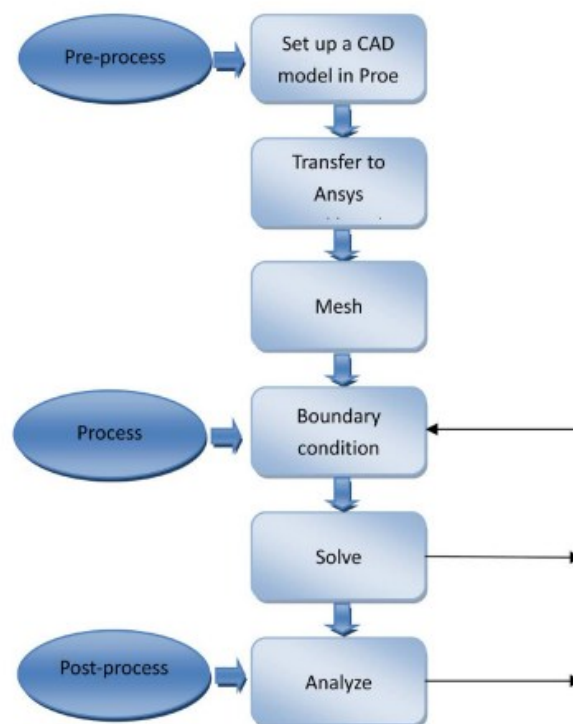


Figure 16 FEM flow diagram [54]

Figure 16 shows the FEM workflow, including CAD modeling, meshing, boundary conditions, solving, and result analysis, ensuring accurate simulations for MEX.

## 5.4 Simulation set up

This section outlines the simulation procedure used in Ansys Polyflow.

### 5.4.1 Geometry

The simulation was based on the geometry (see Figure 17) of the E3D V6 extruder, featuring a nozzle with a 0.6 mm die diameter. A 3D model of the nozzle was created in CAD software to reflect the actual E3D V6 design. This model was then imported into Ansys for further meshing and simulation.

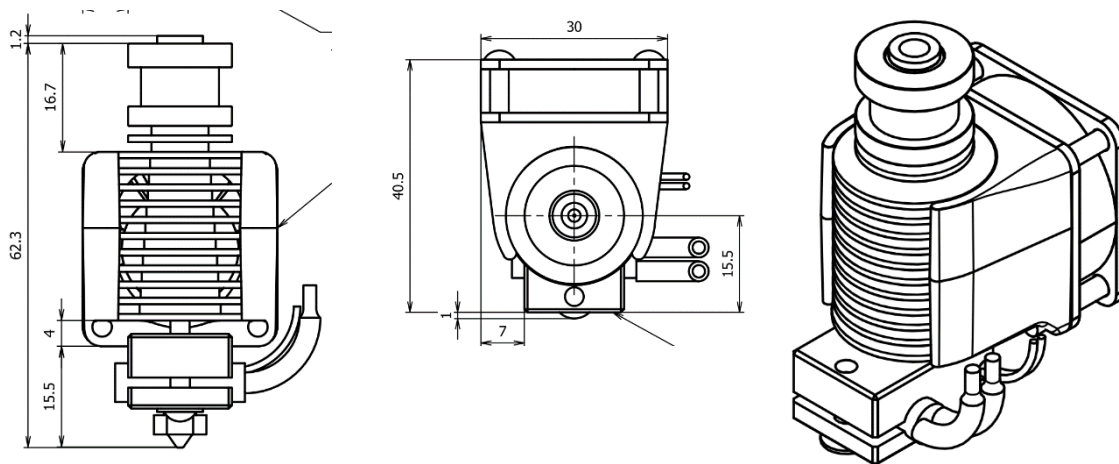


Figure 17 Nozzle geometry [55]

The construction includes several components: the heat sink, heat block, nozzle, and heat source. Additionally, a PTFE tube was integrated into the system for force measurement and was also modeled in the simulation.

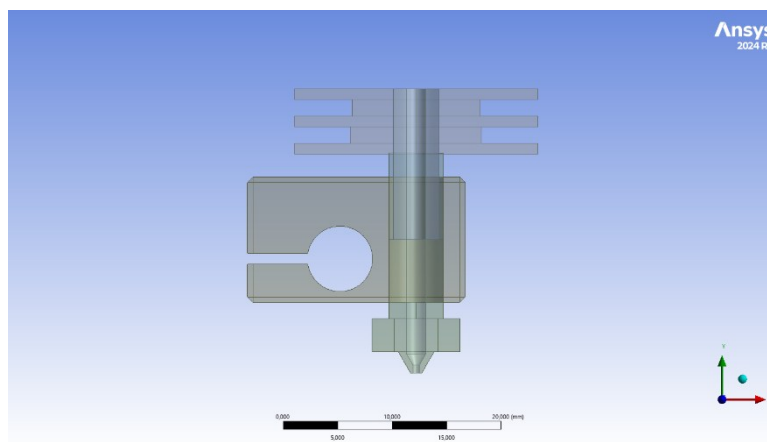


Figure 18 Simulation model construction into Ansys

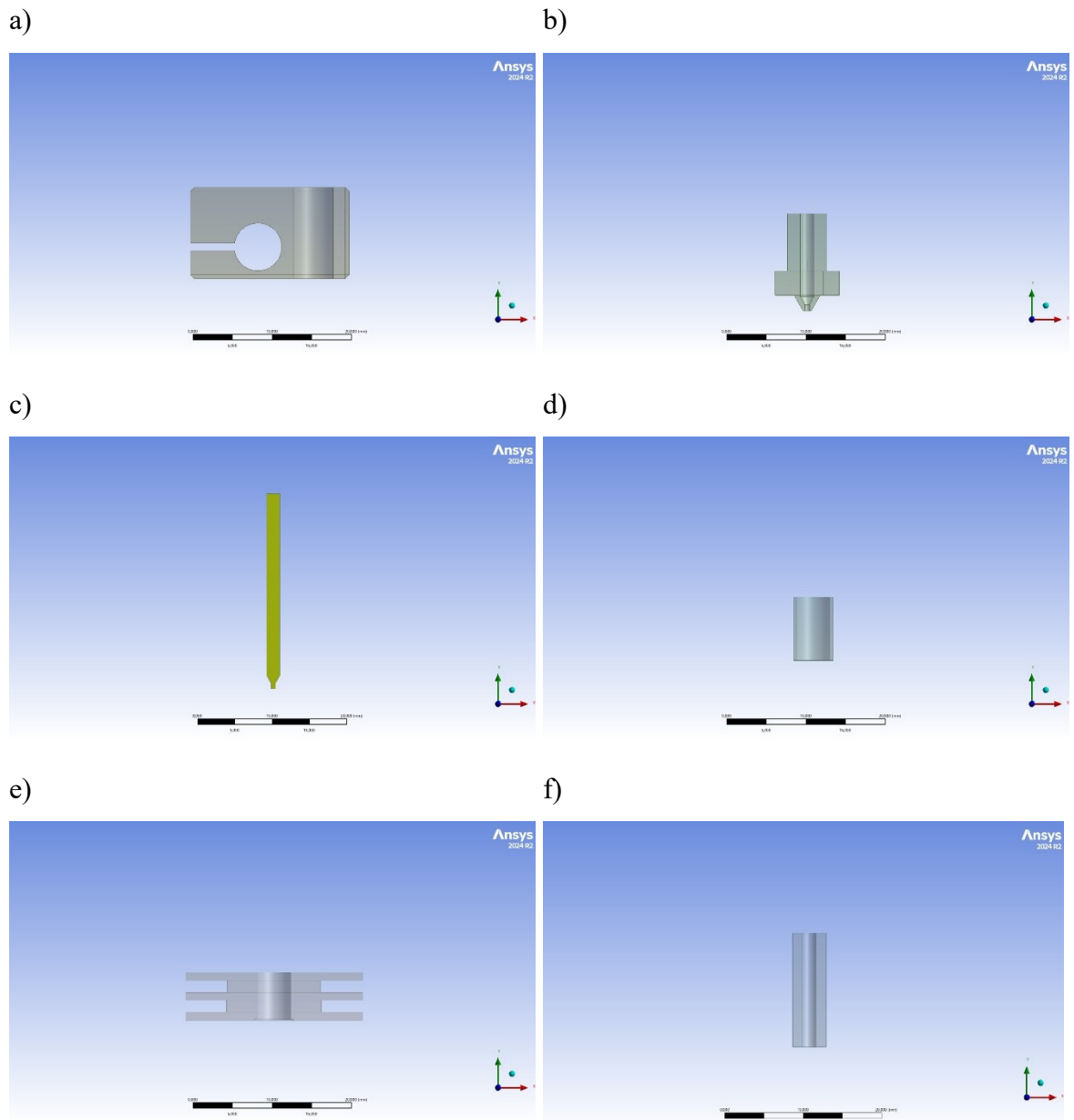


Figure 19 Individual parts for E3D die: a) heat source, b) nozzle, c) melt, d) heat break, e) sink, f) PTFE tube.

In Ansys Polyflow, the geometry of the die was constructed based on the actual design (Figure 19). The upper section of the heat sink was removed. To reduce further computation time, only half of the die was modeled, taking advantage of geometric symmetry.

### 5.4.2 Meshing

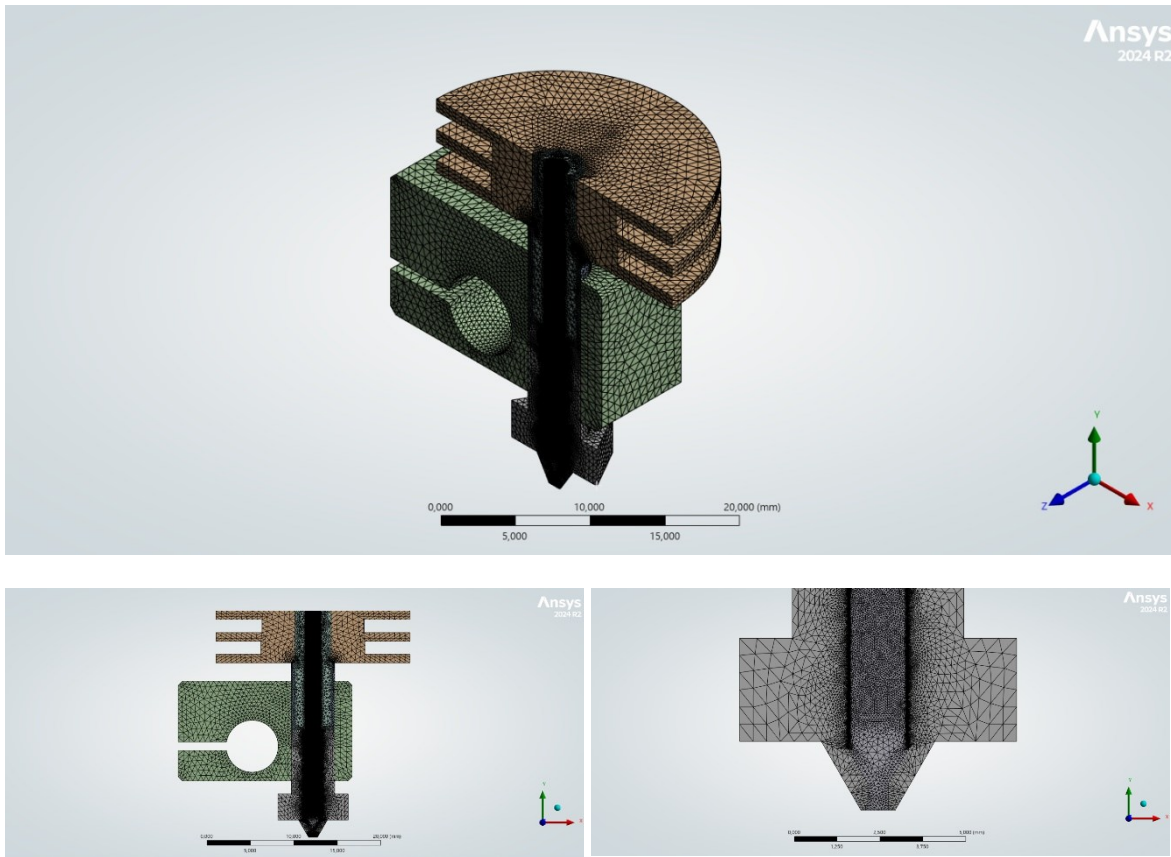


Figure 20 3D View of the Overall Mesh and Nozzle Region

The mesh consisted of 96 436 elements and 180 464 nodes, element size 0.05mm.

For accurate simulation results, material data must be defined for each component included in the geometry. These properties are assigned during the simulation setup and directly affect heat transfer and flow behavior.

| Property                        | Steel (1.4301) | PTFE           | Aluminium     | Brass (CW614N) |
|---------------------------------|----------------|----------------|---------------|----------------|
| Density (kg/m <sup>3</sup> )    | 7900 at 20 °C  | 2200 at 20 °C  | 2700 at 0 °C  | 8470 at 20 °C  |
| Thermal conductivity (W/m·K)    | 18 at 200 °C   | 0.26 at 100 °C | 236 at 0 °C   | 131 at 200 °C  |
| Specific heat capacity (J/kg·K) | 530 at 200 °C  | 1230 at 200 °C | 984 at 200 °C | 410 at 20 °C   |

Table 9 Thermal properties of materials [56]

### 5.4.3 Set up

The simulation was performed assuming a generalized Newtonian, non-isothermal flow. Two different wall boundary conditions were considered: Slip model, full wall adhesion.

### 5.4.4 Slip model

For the slip condition (see Figure 21), the generalized Navier slip law was applied, and it is give by equation 12:

$$f = F(v) \cdot H(T) \cdot G(p) \quad (12)$$

Where:  $F(v)$  generalized Navier's law,  $H(T)$  Arrhenius temperature dependence,  $G(p)$  pressure-independent function. The function  $F(v)$  is further defined in equation 13:

$$F(v) = -k \cdot (v_r)^e \quad (13)$$

Where:  $k = 1.0 \cdot 10^7$ ,  $e = 1$

The slip model was applied along the PTFE tube and within the die section. For the wall adhesion case, the boundary condition was set to zero wall velocity, representing full sticking. The effects of both conditions are compared and discussed in the results section, based on the formulations in For the slip condition (see Figure 21), the generalized Navier slip law was applied, and it is give by equation 12 and equation 13.

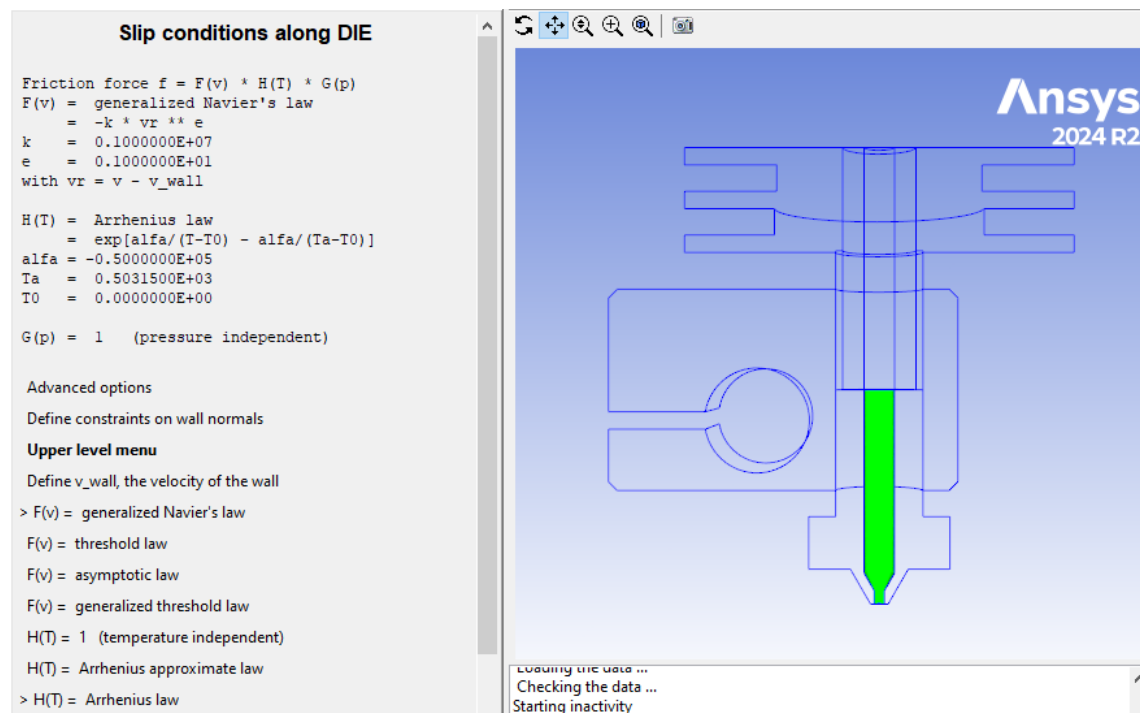


Figure 21 Definition of slip boundary conditions and die region selection in Ansys Polyflow

### 5.4.5 Boundary Conditions

Melt flow conditions, the domain is provided in (Figure 19 c)

The simulation was based on a non-isothermal, shear-dependent flow through the E3D nozzle geometry. The inlet volumetric flow rate was set to  $1.44317 \cdot 10^{-8} \text{ m}^3/\text{s}$ , which is half of the maximum flow rate of the experimental reached values. Only half, as we are only simulating half of the geometry. The viscosity of the ABS melt was described using the Cross model with Arrhenius-type temperature dependence, as detailed in Table 10. Material properties used for the simulation, including density, thermal conductivity, and specific heat capacity, are summarized in Table 11.

Viscosity modeling

| Parameters                 | Value         |
|----------------------------|---------------|
| Viscosity model            | Cross model   |
| Pre-factor (fac)           | 627.545       |
| Characteristic time (tnat) | -0.232        |
| Power-law index (expom)    | -0.6389       |
| Temperature dependence     | Arrhenius law |
| Activation energy (a)      | 1079.6        |
| Reference temperature (Ta) | 503.15K       |

Table 10 Viscosity model for Polyflow of the ABS melt

Material Properties

| Property                           | Value                    |
|------------------------------------|--------------------------|
| Density ( $\rho$ )                 | 961.73 kg/m <sup>3</sup> |
| Thermal conductivity ( $\lambda$ ) | 0.196 W/(m·K)            |
| Specific heat capacity (Cp)        | 2108.08 J/(kg·K)         |

Table 11 Material data for Polyflow of the ABS melt

#### Thermal Boundary Conditions:

The inlet temperature was defined as 313.15 K (40 °C) to represent the melt entry point. Three die temperatures were used to simulate different processing conditions: 503.15 K, 523.15 K, and 543.25 K.

#### Flow Boundary Conditions:

At the outflow, no external forces were applied. The model included a mid-plane symmetry condition, assuming no tangential forces or normal velocities. Two wall boundary

approaches were tested: one using a slip model with temperature-dependent wall behavior, and the other assuming full wall adhesion, where the wall velocity was set to  $v_{wall} = 0$ .

The impact of both boundary conditions is further analyzed in the results section.

The other domains consist of the nozzle including internal interfaces, symmetry boundaries, and an applied heat flux condition. The PTFE tube primarily contains interfaces with the melt and the heat break, additionally, a symmetry boundary is applied. At the upper side the temperature is set to 313.15 K. The sink is cooled by forced convection from a fan. The heat break connects the heating block to the sink and nozzle. It includes interfaces with adjacent parts and a symmetry boundary. And the heat source represents the heating block of the system. It includes internal interfaces and symmetry conditions. A set constant temperature was applied, depending on the settings at the heating surface.

The material data is collected in Table 12.

| Domain                 | Nozzle | PTFE   | Break  | Sink      | Block |                   |
|------------------------|--------|--------|--------|-----------|-------|-------------------|
| Material               | Brass  | PTFE   | Steel  | Aluminium |       | Unit              |
| Density                | 8470   | 2200   | 7900   | 2700      |       | kg/m <sup>3</sup> |
| Thermal conductivity   | 131    | 0.23   | 13     | 236       |       | W/(m·K)           |
| Specific heat capacity | 410    | 1230   | 530    | 984       |       | J/kg              |
| Average temperature    | 300    | 313.15 | 313.15 | 313.15    |       | K                 |

Table 12 Material data for Polyflow of the the solid parts [56]

## **PRACTICAL PART**

## 6 RESULTS

The following section provides an overview of the results obtained from the material tests and the numerical simulations.

### 6.1 DSC

The DSC curve (Figure 22 a) of Ultrafuse ABS shows a clear glass transition around 105 °C, typical for amorphous polymers. No melting peak was observed, confirming its non-crystalline nature. A slight hysteresis between heating and cooling curves indicates thermal relaxation effects.

For Ultrafuse 316L (Figure 22 b) a sharp endothermic peak appears between 180–200 °C during heating, representing the melting of the polymer binder. This temperature range is characteristic of the melting of the crystalline regions within the semi-crystalline polymer binder. A corresponding exothermic peak is seen on cooling, confirming binder solidification. No thermal transitions related to the metal content were detected within the tested range.

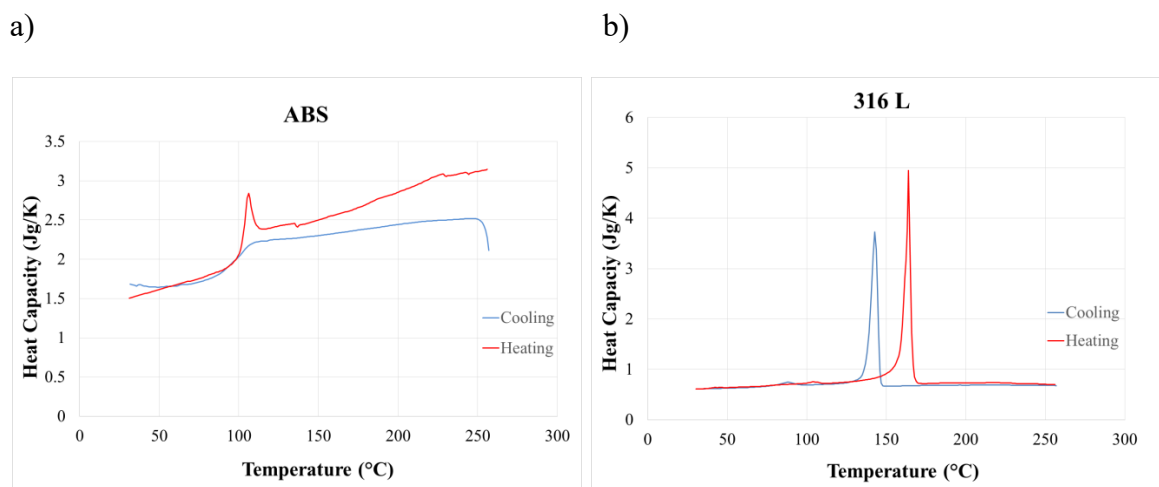


Figure 22 DSC (heat capacity measurement of Ultrafuse ABS and Ultrafuse 316L)

### 6.2 Density

The pvT results show distinct thermal behaviors for Ultrafuse ABS and Ultrafuse 316L. Ultrafuse ABS in (Figure 23) exhibits a continuous increase in specific volume with temperature, typical of amorphous polymers. The data indicate stable thermal expansion without any clear phase transitions in the tested range.

In contrast, Ultrafuse 316L (Figure 24) displays a pronounced volume shift around 150–160 °C, indicating a semi-crystalline phase change in the polymeric binder. The presence of metal fillers significantly reduces the material’s compressibility, resulting in lower specific volumes and steeper response curves.

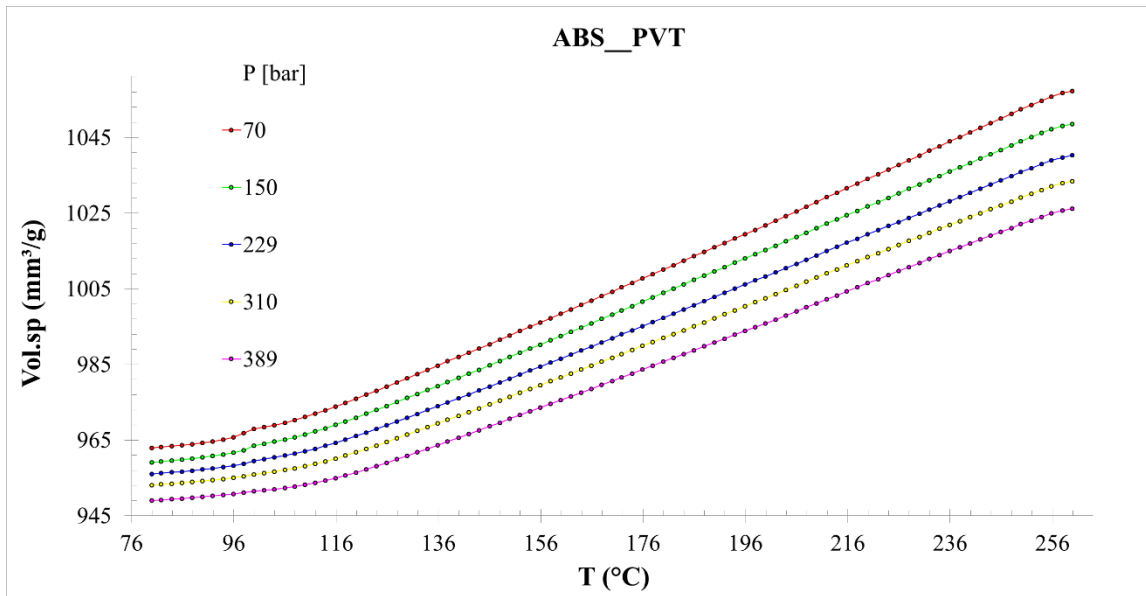


Figure 23 pVT of Ultrafuse ABS

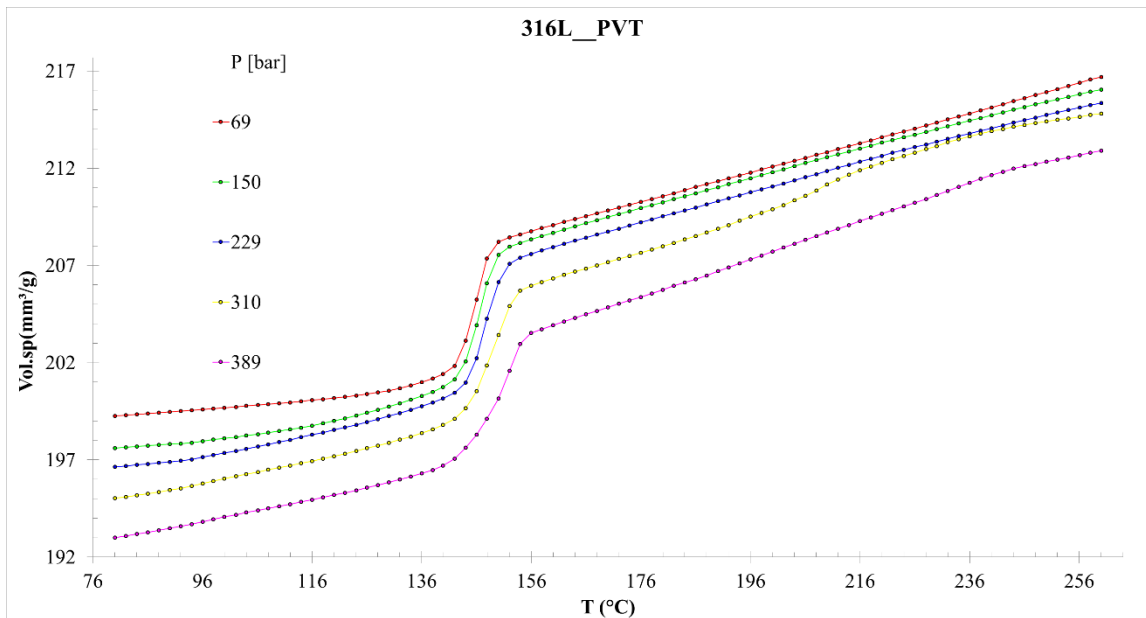


Figure 24 pVT of Ultrafuse 316L

### 6.3 Thermal conductivity

The thermal conductivity of Ultrafuse ABS and Ultrafuse 316L was evaluated at three temperatures: 210 °C, 230 °C, and 250 °C. The measurements (Figure 25) show that Ultrafuse 316L exhibits significantly higher thermal conductivity values compared to ABS at all tested temperatures. This is attributed to the high metal content in the 316L composite, which enhances the heat transfer.

For ABS, the thermal conductivity remains relatively constant, see Table 13 Measured thermal conductivity ( $\lambda$ ) of Ultrafuse ABS and Ultrafuse 316L at selected temperatures. with only slight variation across the temperature range. In contrast, Ultrafuse 316L shows a gradual decrease in thermal conductivity with increasing temperature, likely due to changes in the binder's thermal properties or increased thermal resistance at higher temperatures.

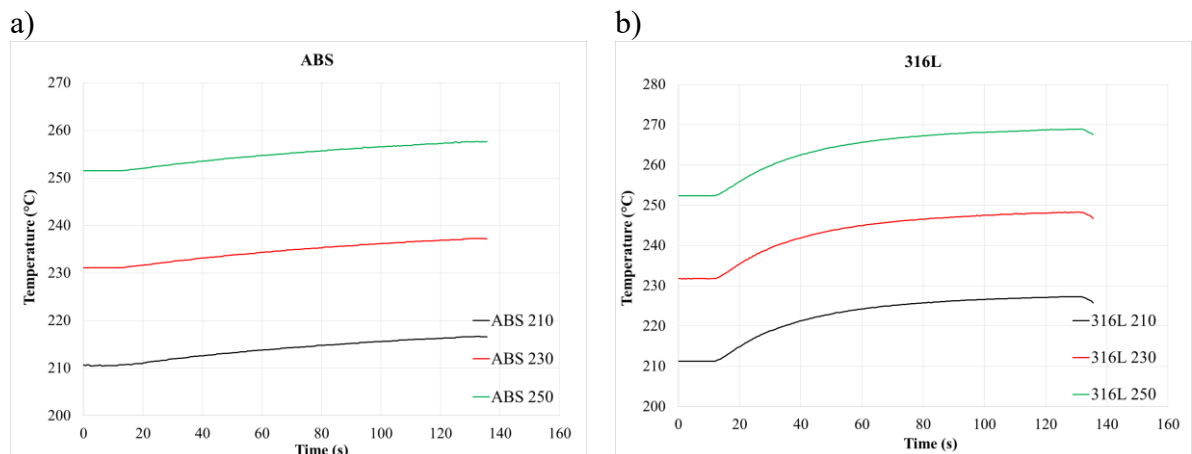


Figure 25 Temperature over time curves of Ultrafuse ABS and Ultrafuse 316L

Experiments showed that the lower thermal conductivity of Ultrafuse ABS led to higher extrusion forces during feeding, as heat transfer was less efficient compared to Ultrafuse 316L. This affected melt pool formation and required greater force to maintain material flow. The following Table 13 presents the measured thermal conductivity values for both materials.

| Name    |     | Ultrafuse ABS | Ultrafuse 316L |
|---------|-----|---------------|----------------|
| T       | T   | Lambda        |                |
| K       | °C  | W/(m·K)       |                |
| 483.15  | 210 | 0.198         | 1.489          |
| 503.15  | 230 | 0.195         | 1.369          |
| 523.15  | 250 | 0.195         | 1.350          |
| Average |     | 0.196         | 1.403          |

Table 13 Measured thermal conductivity ( $\lambda$ ) of Ultrafuse ABS and Ultrafuse 316L at selected temperatures.

## 6.4 Rheological properties

This graph (Figure 26) illustrates the measured viscosity data for ABS at temperatures of 210 °C, 230 °C, and 250 °C. The viscosity clearly decreases as shear rate increases, indicating shear-thinning behavior common in polymer melts. These direct measurements serve as baseline experimental data for subsequent analysis and modeling.

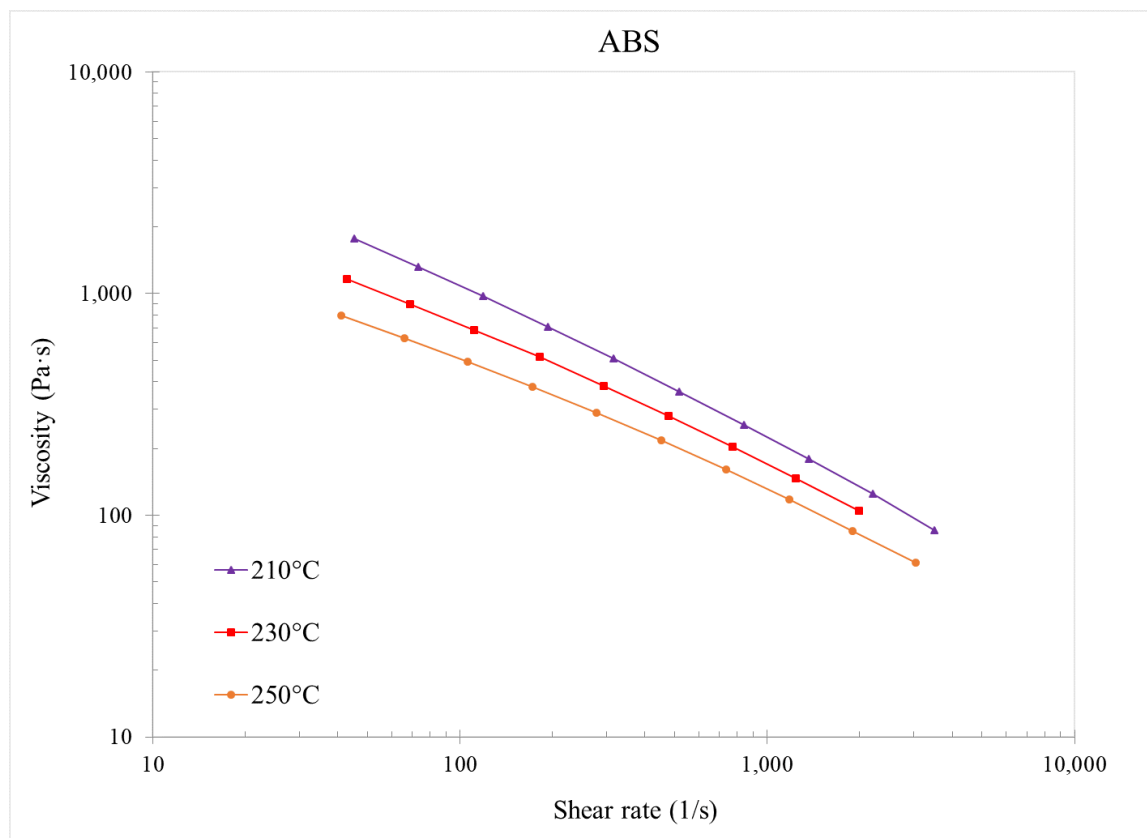


Figure 26 Viscosity of ABS at measured temperatures

The second graph (Figure 27) presents ABS viscosity curves obtained with the temperature shift according to the Arrhenius model (In equation 5). Solid lines show curves approximated by the Cross-Arrhenius shear stress model, while measured data at 210 °C and 250 °C appear as discrete points. The extrapolated curves at 50 °C and 100 °C are derived from these measured data. Constants obtained from this extrapolation were directly applied in numerical simulations to predict viscosity at conditions beyond the original experimental range.

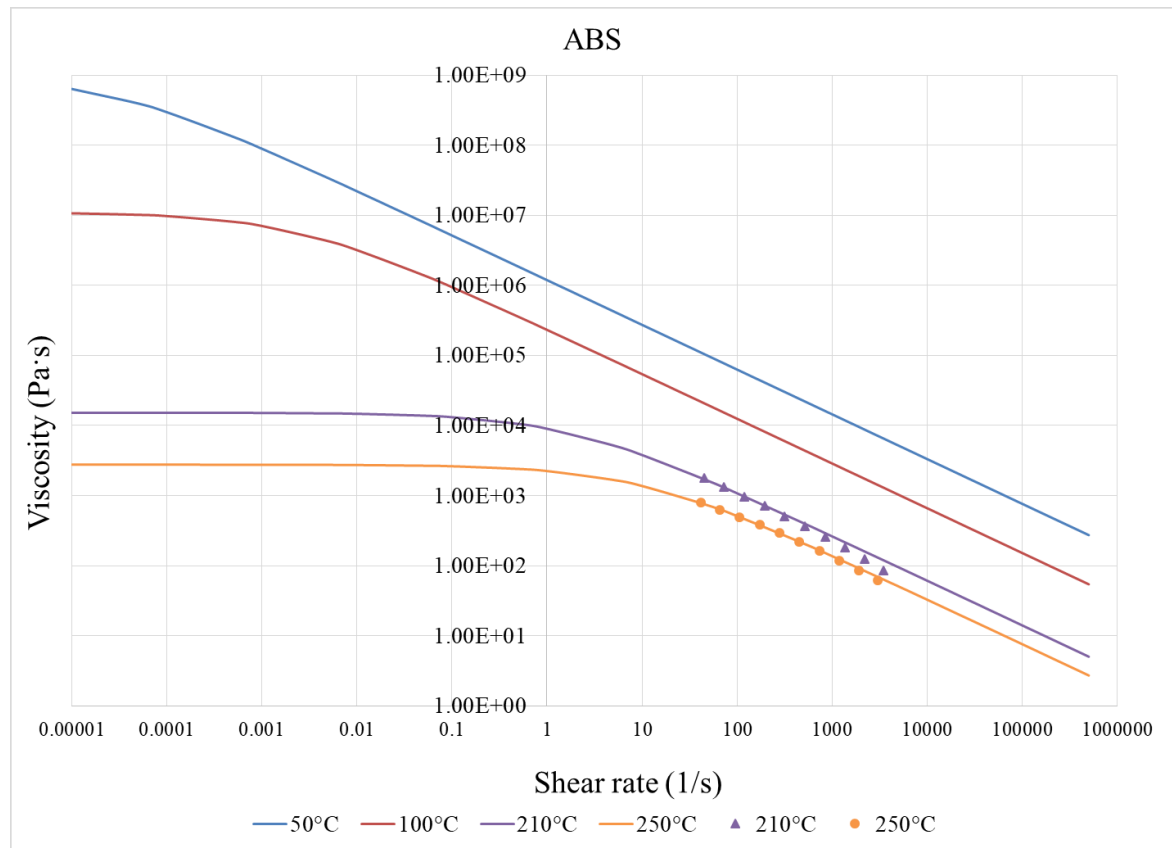


Figure 27 Temperature shift of ABS

The Table 14 presents constants derived from viscosity graphs using the Cross-Arrhenius shear stress model. Parameter A represents zero shear viscosity, indicating the material's viscosity at low shear rates. Parameter B is a time constant associated with the onset of shear-thinning behavior. Parameter C is a dimensionless exponent defining the slope of the shear-thinning region. Parameters  $T_0$  and  $\alpha$  serve as temperature-dependent shift factors, describing how viscosity changes with temperature. These constants were calculated from experimental ABS viscosity data and applied directly in simulations to predict viscosity behavior beyond measured temperature and shear rate conditions.

|          |             |      |
|----------|-------------|------|
| A        | 6275.448243 | Pa·s |
| B        | 0.232060494 | s    |
| C        | 0.638899503 | /    |
| $T_0$    | 503.15      | K    |
| $\alpha$ | 10792.76    | K    |

Table 14 Parameters for ABS

Figure 28 provides measured viscosity curves for Ultrafuse 316L at 210 °C, 230 °C, and 250 °C, demonstrating similar shear-thinning behavior. Attempts to extrapolate additional temperatures for simulations were unsuccessful due to data variability and lack of literature references. However, these measured results were validated through independent testing at another university. Consequently, a material model was developed based exclusively on direct measurements, without reliance on extrapolated data.

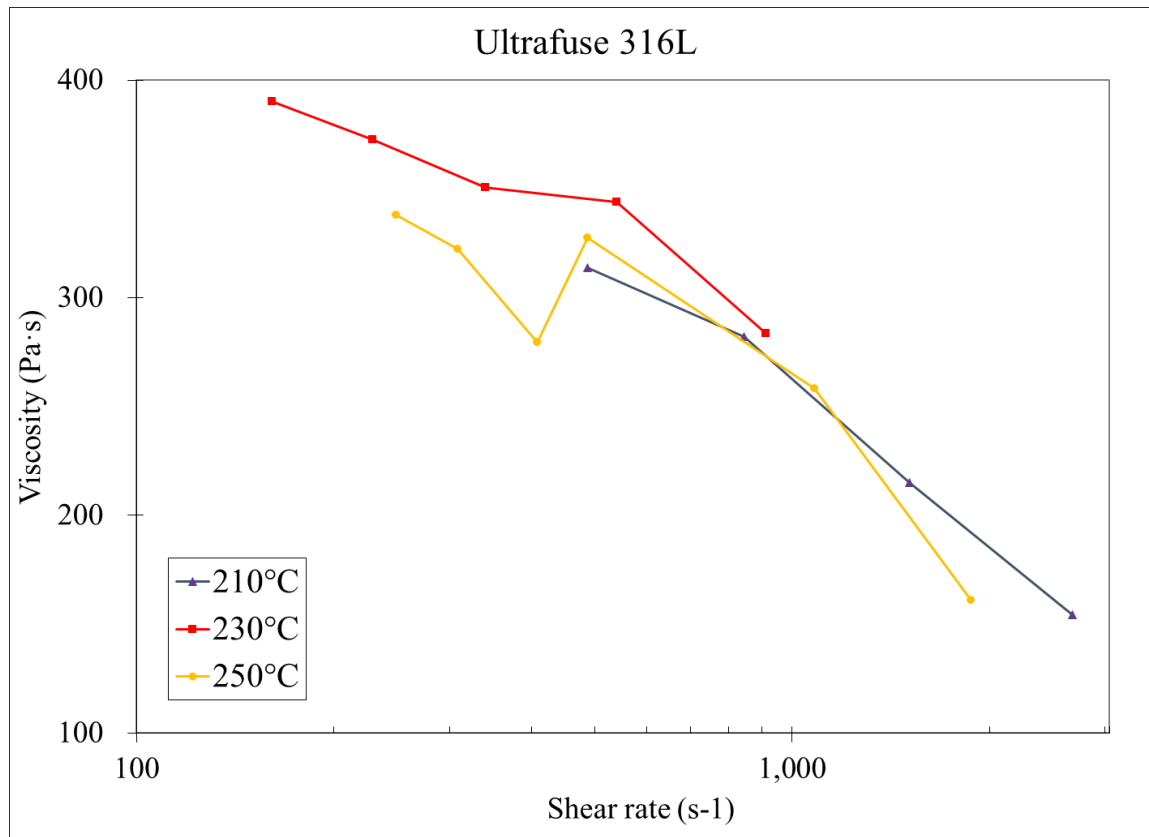


Figure 28 Measured viscosity curves of Ultrafuse 316L

## 6.5 Extrusion Force Measurement in MEX

Force measurements were conducted using a load cell mounted beneath the extruder head to analyze the extrusion behavior of Ultrafuse ABS and Ultrafuse 316L materials (see Figure 29). The results indicated consistent and analogous force development trends across various velocities for ABS at temperatures of 230 °C, 250 °C, and 270 °C. Conversely, the extrusion force for 316L exhibited instability and lower consistency due to the powder-based composition of the filament.

Maximum measured forces reached approximately 60 N for ABS, while 316L demonstrated a significantly lower maximum force of approximately 35 N. In several cases, negative force values were recorded during 316L extrusion. These negative readings likely resulted from temporary force instabilities after prolonged extrusion, possibly due to filament slipping, local clogging, or inconsistent material feeding caused by the metal-powder-binder mixture.

This discrepancy highlights material-specific behavior under extrusion conditions. It underscores the need to adapt processing parameters such as feeding rate, nozzle temperature, and extrusion length to the characteristics of each material for stable performance.

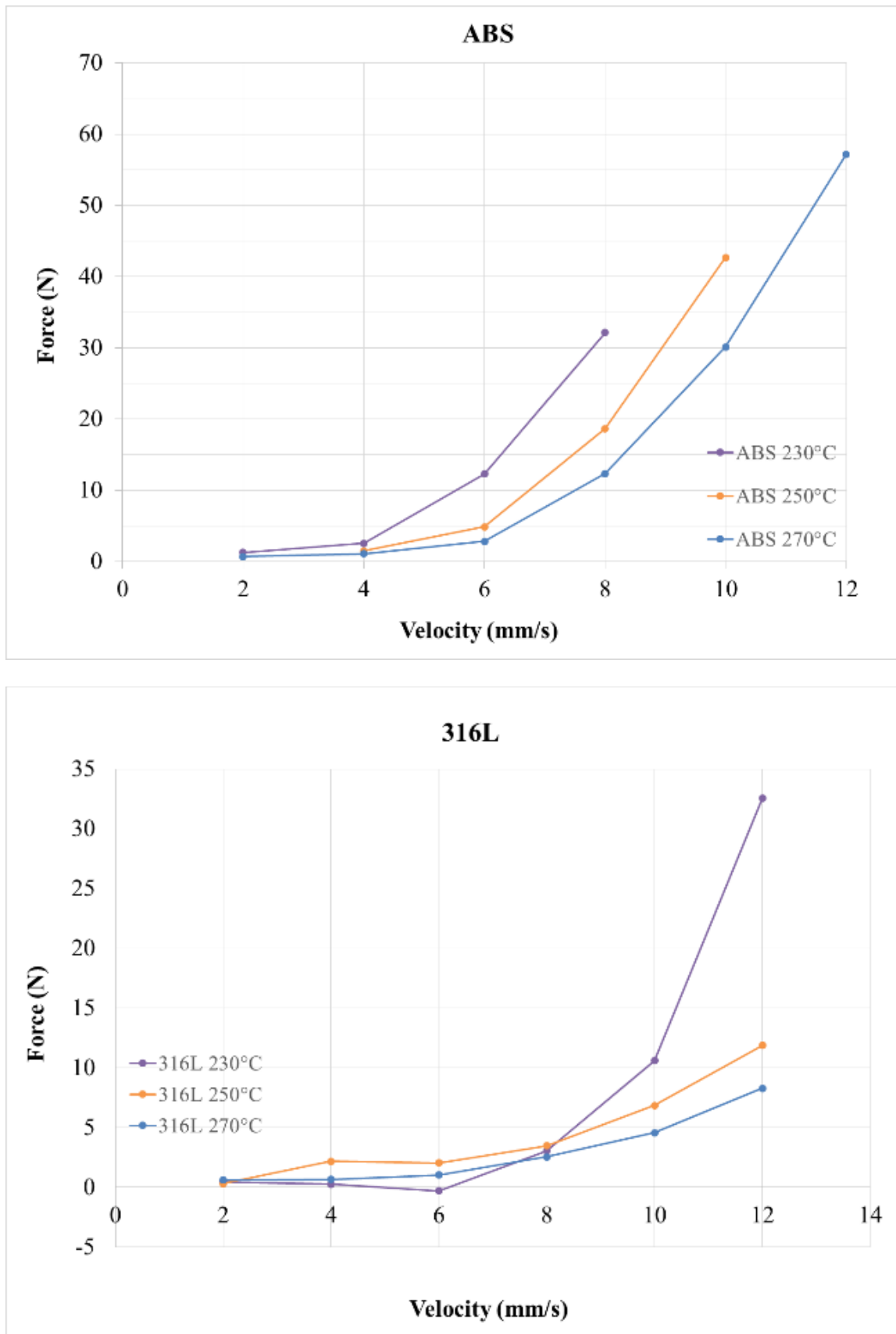


Figure 29 Force graphs for ABS and 316L

## **7 NUMERICAL SIMULATIONS OF EXTRUSION PROCESS**

This section presents the ABS simulation results for the E3D die. Key characteristics such as temperature, velocity, shear rate, and viscosity were extracted from the simulation at three processing temperatures: 230 °C, 250 °C, and 270 °C. The results are displayed in both pictures and graphs. Since the simulation was conducted using six incremental steps, each step corresponds to a specific filament velocity: 2, 4, 6, 8, 10, and 12 mm/s, respectively. In the figures, these are labeled as “Expression 1” through “ 6,” with expression 1 representing the lowest velocity and 6 the highest.

### **7.1 Simulation Wall Slipping.**

#### **7.1.1 Temperature**

To avoid visual overload, only the temperature distributions at 230 °C and 270 °C are shown, as the results at 250 °C follow a similar trend.

##### **Results 230 °C**

At lower velocities, heat is transferred more evenly throughout the filament path, resulting in a more uniform temperature profile. In contrast, at higher velocities, the filament travels faster through the heating zone, reducing residence time and leading to less effective heat transfer. This results are shown Figure 30 in a cooler core and more pronounced thermal gradients across the flow field.

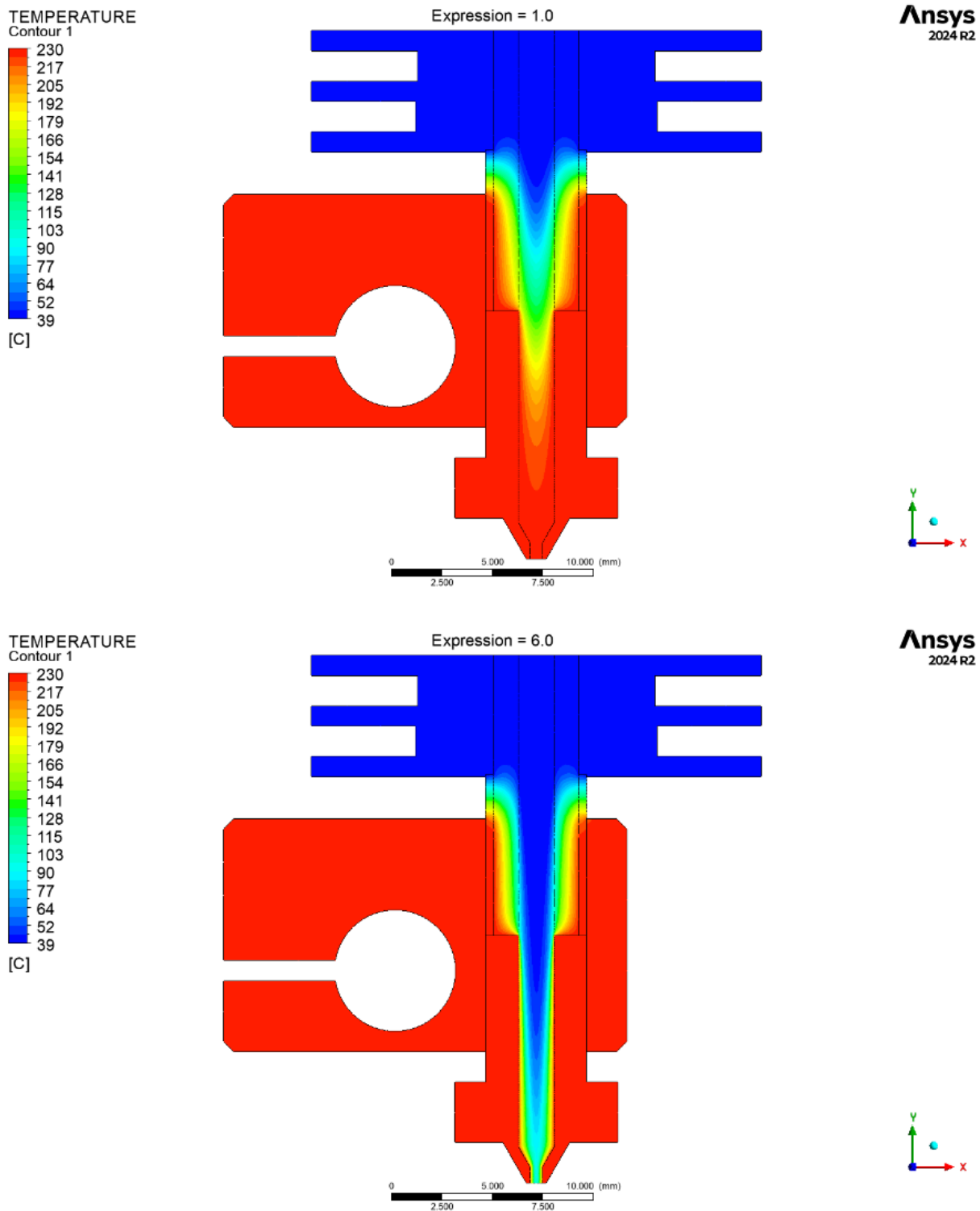


Figure 30 Temperature distribution at different filament feeding velocities for 230 °C. The top image corresponds to the lowest velocity (2 mm/s), while the bottom image represents the highest velocity (12 mm/s).

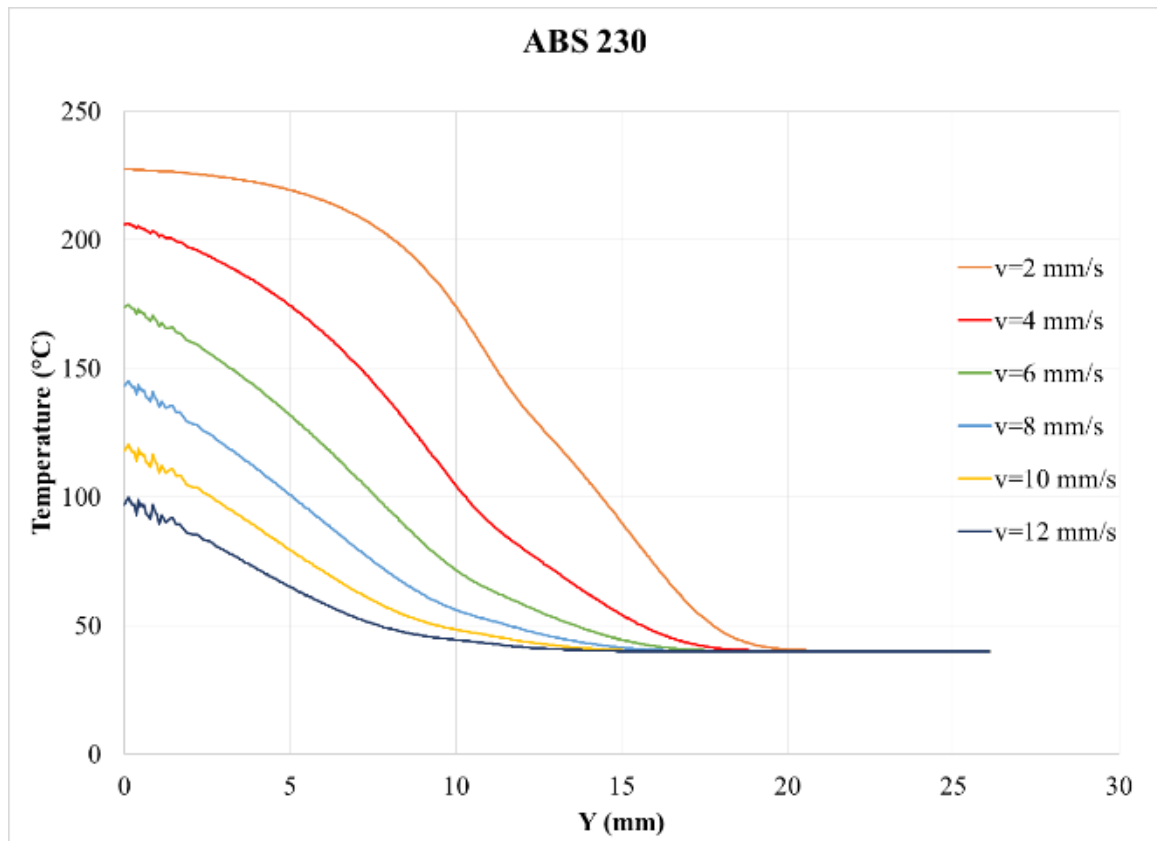


Figure 31 Temperature distribution along the die at 230 °C for different feed rates.

Each curve of Figure 31 represents a different feed rate, ranging from 2 mm/s to 12 mm/s. As the feed rate increases, the filament spends less time in the heated zone, resulting in lower overall temperatures along the flow path. This trend highlights the effect of feed rate on thermal transfer efficiency during extrusion.

### Results 270 °C

As shown in the Figure 32, increasing the filament feeding velocity from 2 mm/s to 12 mm/s results in a narrower and more elongated temperature profile. At higher speeds, the filament has less time to absorb heat from the surrounding components, leading to a cooler core and steeper thermal gradients. This behavior highlights the influence of residence time on temperature distribution within the extrusion zone.

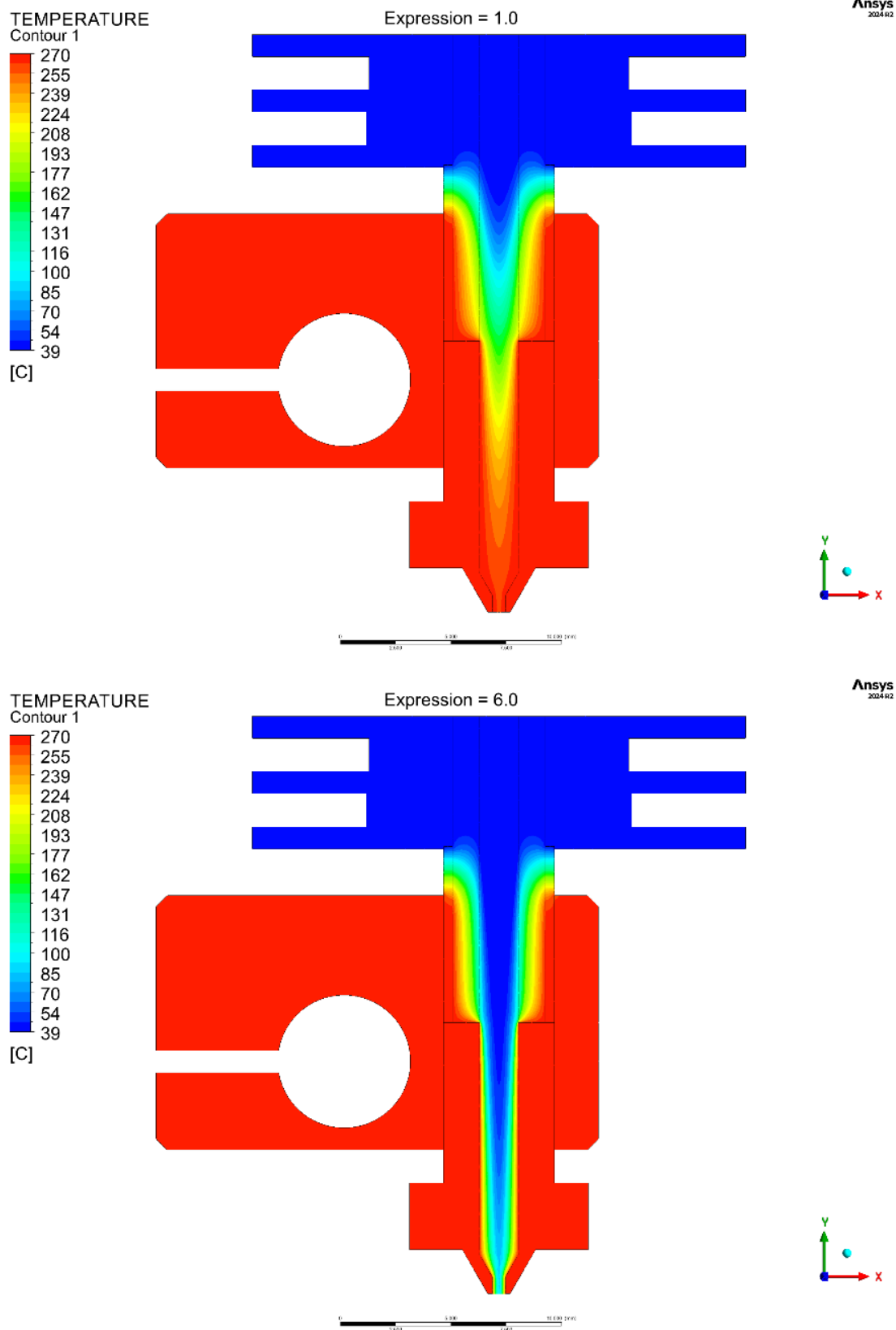


Figure 32 Temperature distribution with different filament feeding for 270 °C. The top corresponds to the lowest velocity (2 mm/s), while the bottom image represents the highest velocity (12 mm/s).

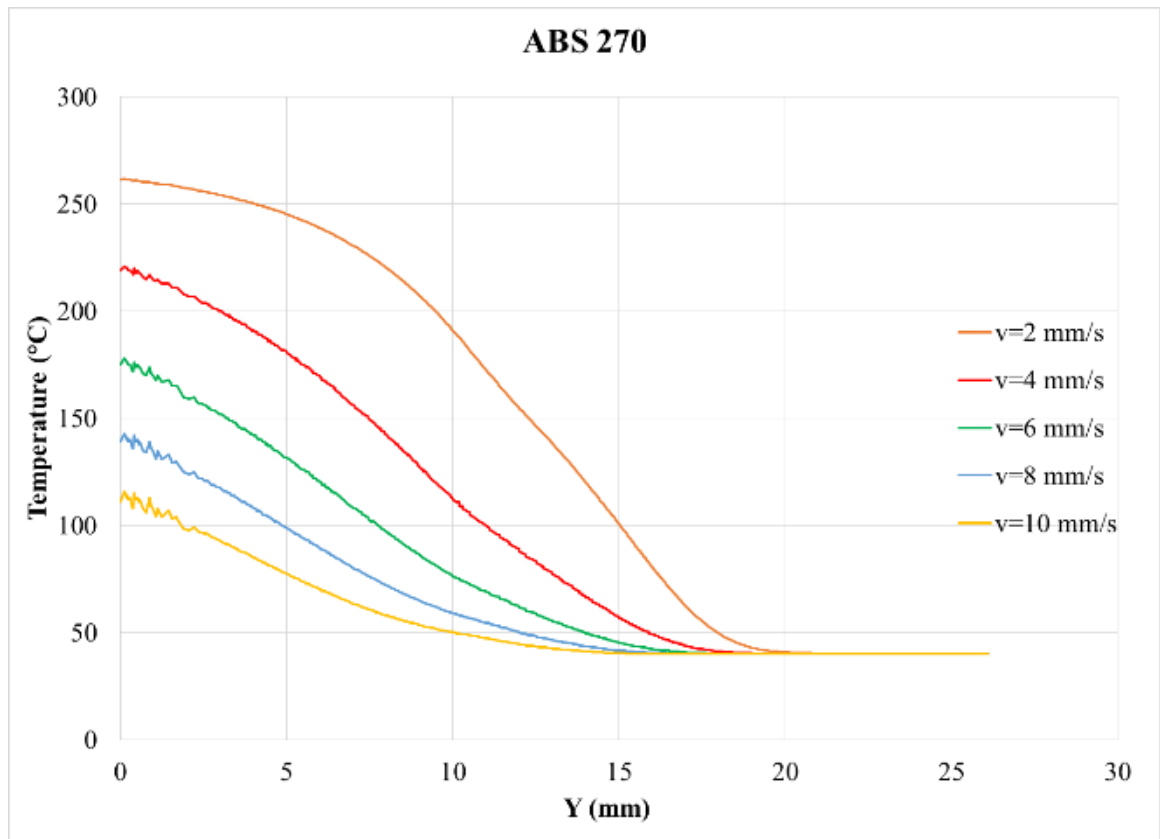


Figure 33 Temperature profiles along the flow direction at 270 °C for varying feed rates

This Figure 33 presents the temperature distribution inside the die at a processing temperature of 270 °C for different feed rates ranging from 2 mm/s to 12 mm/s. Higher feed rates lead to a sharper temperature drop along the flow axis, reflecting limited heating at higher velocities and reduced thermal transfer during extrusion.

### 7.1.2 Velocity

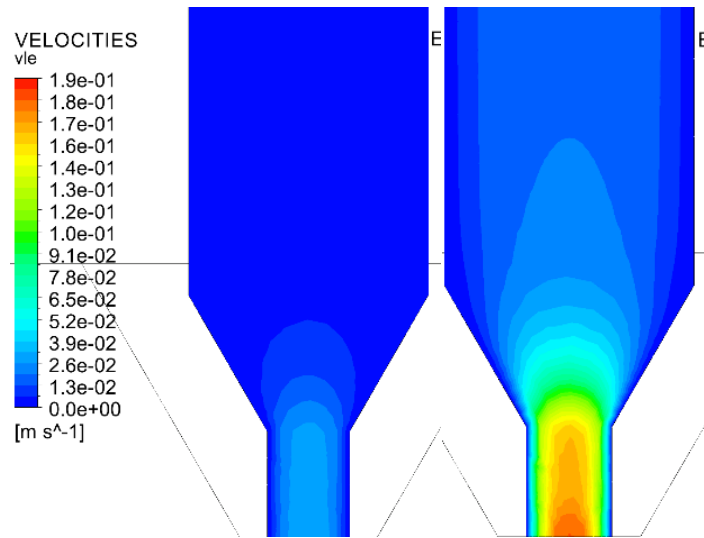


Figure 34 Velocity distribution in the extrusion head at 270 °C. Left 2 mm/s and right 12 mm/s

The left Figure 34 corresponds to the initial feeding step (2 mm/s), while the right image shows the final feeding step (12 mm/s). Both simulations were conducted applying slip boundary conditions.

As expected, the velocity distribution indicates a plug flow behavior in the upper region due to the absence of wall adhesion, where the material remains cooler and more viscous. As the material heats up and flows toward the die, velocity gradients increase, particularly in the narrow die section. The transition from plug flow to wall-adhered flow becomes more pronounced at higher feed rates. This shift occurs along the flow path as speed increases, resulting in higher velocity values concentrated near the die exit.

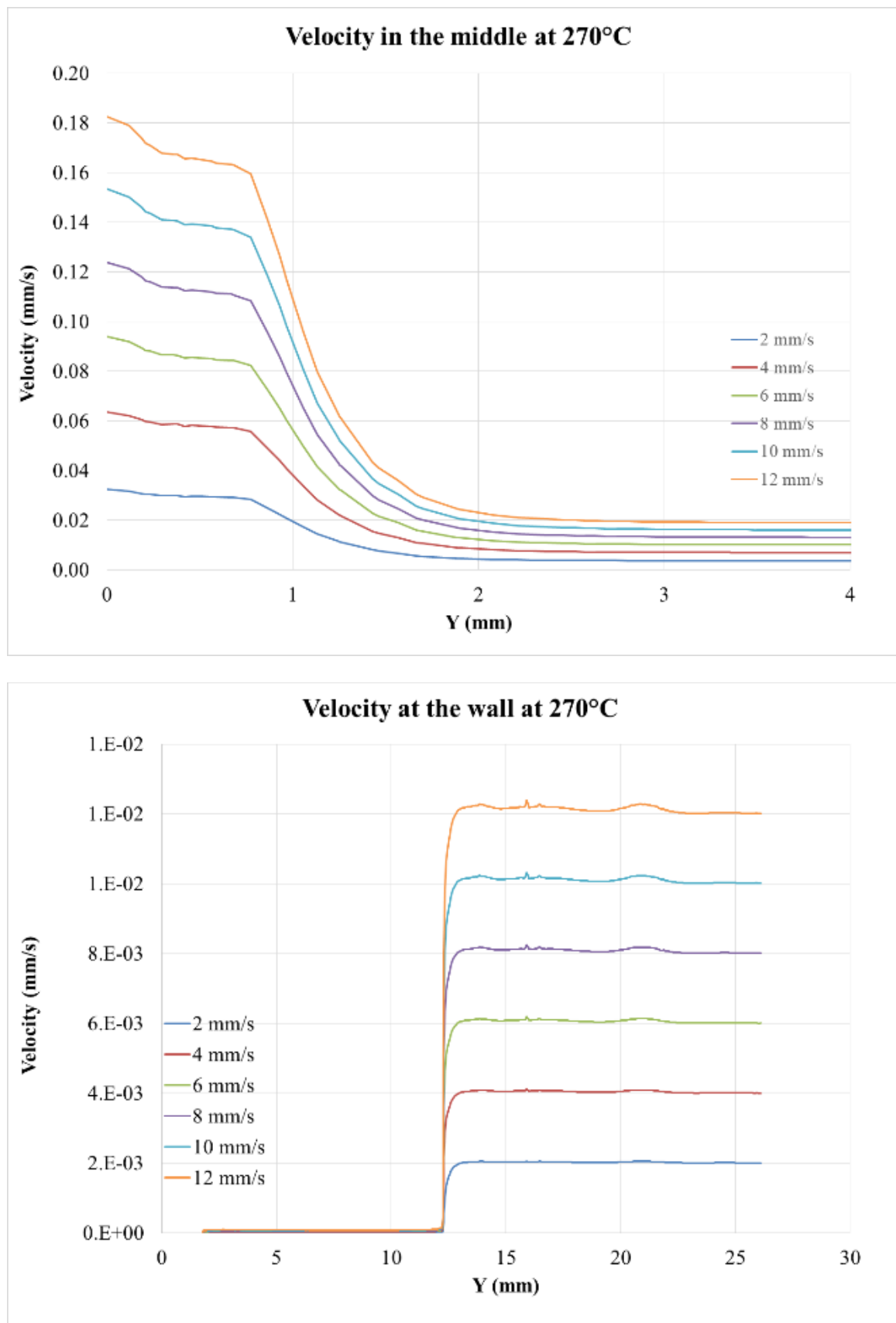


Figure 35 Velocity profiles in the middle (top) and at the wall (bottom) of the PTFE tube at 270 °C for various filament feeding speeds.

The top Figure 35 presents the velocity profile along the central axis of the nozzle. As the filament feed rate increases, the magnitude of velocity increases accordingly. The gradient in this region reflects the transition from a high-shear zone near the inlet to a more stable flow near the nozzle tip.

The bottom Figure 35 shows the velocity distribution at the wall, indicating partial slip behavior. The relatively consistent velocities along most of the wall suggest reduced wall adhesion, which aligns with the imposed slip condition. The abrupt changes near the inlet and outlet reflect localized flow disturbances due to geometry and boundary effects.

## 7.2 Simulation wall adhering

This section shows the influence of wall adhesion on simulation results. Initially, a no-slip condition was applied, assuming full contact between the material and the wall with zero wall velocity. The simulations at 230 °C and 250 °C exhibited similar trends; therefore, for visualization purposes, only the results at 270 °C are presented.

### 7.2.1 Temperature

#### Results 270 °C

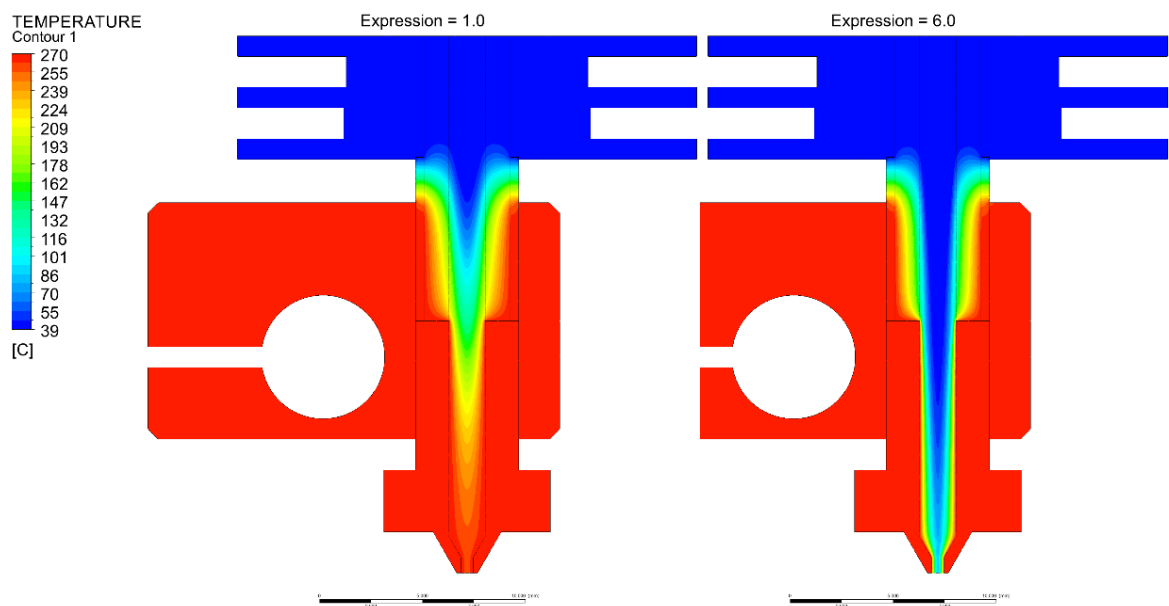


Figure 36 Temperature distribution at 270 °C for simulation with wall adhesion (left: 2 mm/s, right: 12 mm/s).

### 7.2.2 Velocity

The left Figure 37 corresponds to the first feeding step (2 mm/s), and the right image represents the final step (12 mm/s). Wall slip was disabled, assuming full adhesion between the material and the wall.

In this case, the flow profile transitions significantly as the velocity increases. Unlike the plug-like distribution observed with slip conditions, velocity gradients are clearly present near the walls. This indicates that the material is fully adhering to the surface, leading to increased shear and higher velocity differentials across the channel. As the speed increases, the flow becomes more concentrated through the center of the die, consistent with the expected parabolic profile of wall-adhered flow.

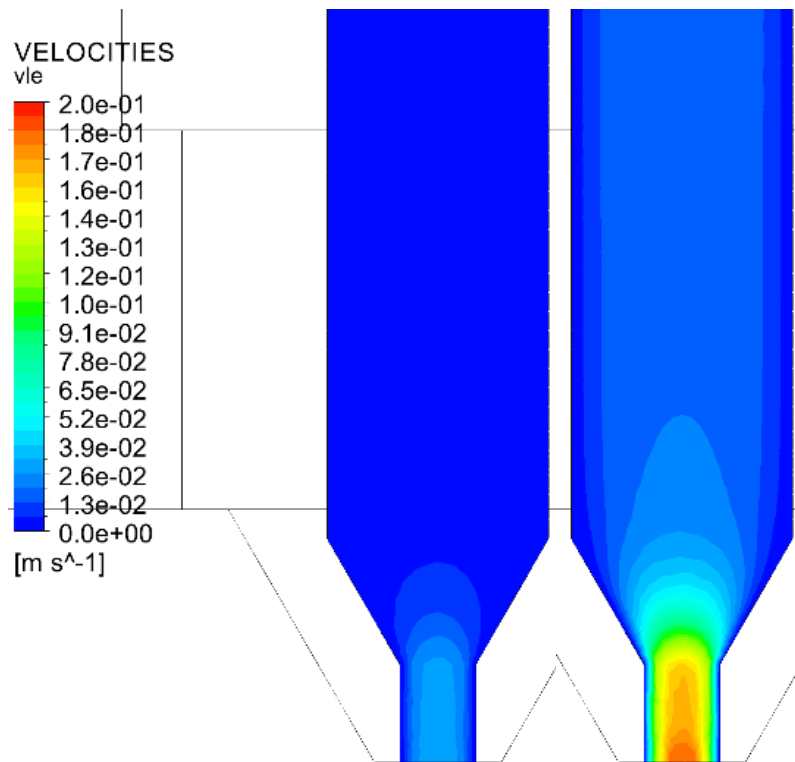


Figure 37 Velocity distribution in the extrusion head at 270 °C with wall adhesion, left 2 mm/s right 12 mm/s

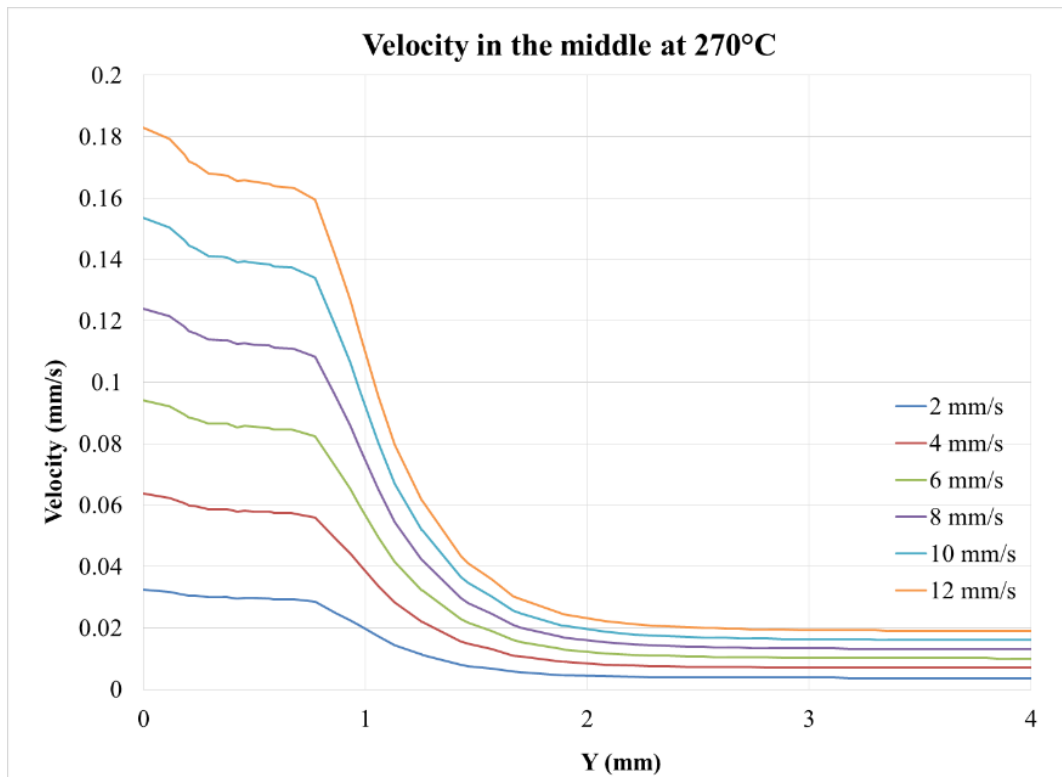


Figure 38 Velocity profiles at 270 °C in the nozzle center with wall adhesion

This Figure 38 illustrates velocity profiles for various feeding speeds at 270 °C under wall adhesion conditions. Unlike the wall-slip scenario, only a single central velocity graph is shown here. This is because, with wall adhesion, the fluid velocity at the wall is strictly zero. Consequently, plotting velocity profiles at the wall region is unnecessary, as no slip velocity exists

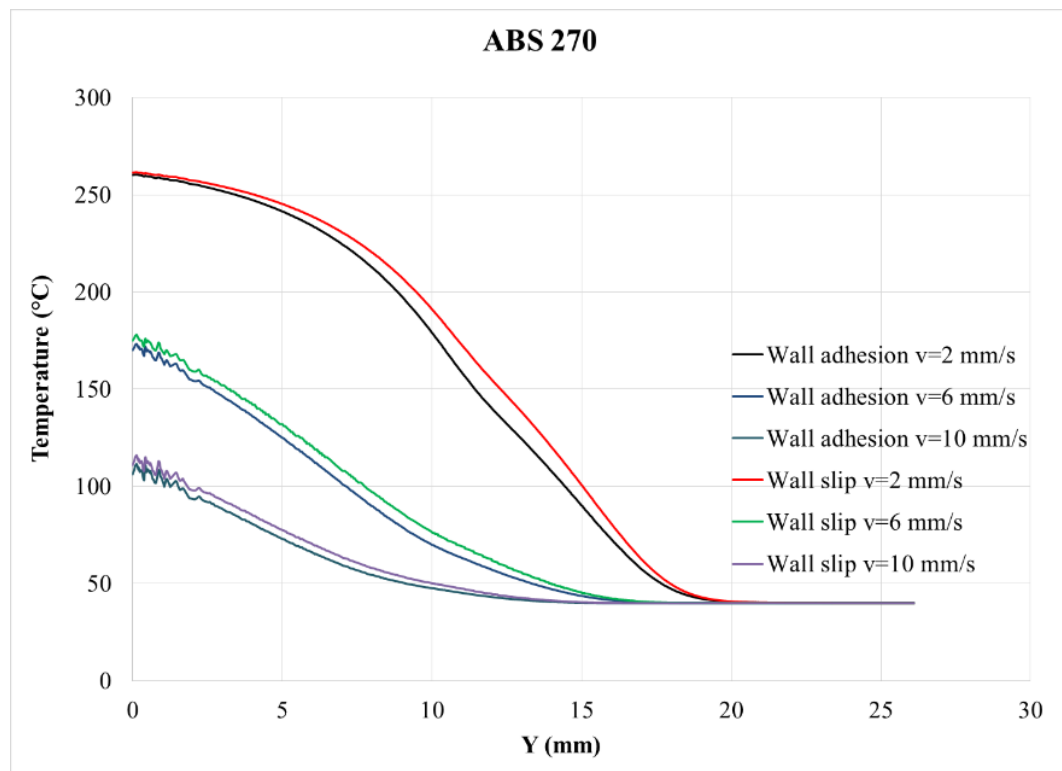


Figure 39 Temperature profiles at 270 °C comparing wall adhesion and wall slip.

The Figure 39 highlights temperature differences resulting from wall adhesion versus wall slip. Speeds of 2, 6, and 10 mm/s were selected to clearly show how slip conditions affect temperature profiles inside the nozzle.

## 8 SIMULATION–EXPERIMENT CORRELATION AND ANALYSIS

### 8.1 Wall slip set up result

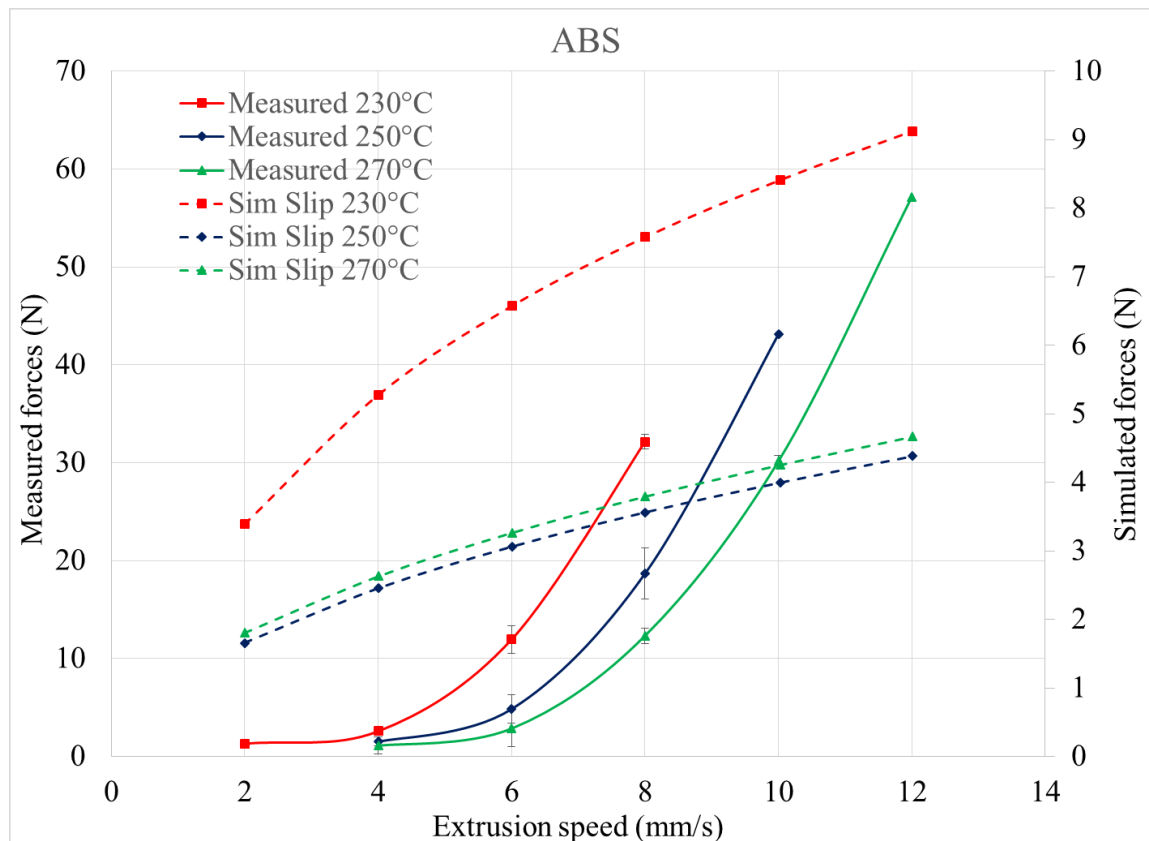


Figure 40 Comparison of simulated and measured extrusion forces for Ultrafuse ABS at different temperatures using wall slip boundary condition.

The results presented in Figure 40 compare the measured extrusion forces with those obtained from simulations using a wall slip boundary condition. Since wall slip was applied along both the PTFE section and the die wall, this likely led to lower predicted forces. The simulation path used here is correct but could be refined. It captures the overall extrusion behavior, yet the predicted forces consistently underestimate the experimental values. This difference becomes more significant at higher velocities, especially at 250 °C and 270 °C, where the simulated forces are surprisingly low. The deviation may result from limitations in the wall slip model, which may not fully reflect the actual interaction between the filament and the die wall. Furthermore, the thermal conductivity and viscosity values used in the simulation could require adjustment, as they strongly affect melt flow and pressure development.

To improve the accuracy, future simulations should consider using a temperature-dependent wall slip model, better fitting of viscosity data at low shear rates, and potentially accounting for more realistic heat transfer effects, such as non-uniform heating and thermal contact resistance. Calibration against a broader set of experimental conditions could also enhance the predictive capability of the model.

## 8.2 Wall adhesion set up result

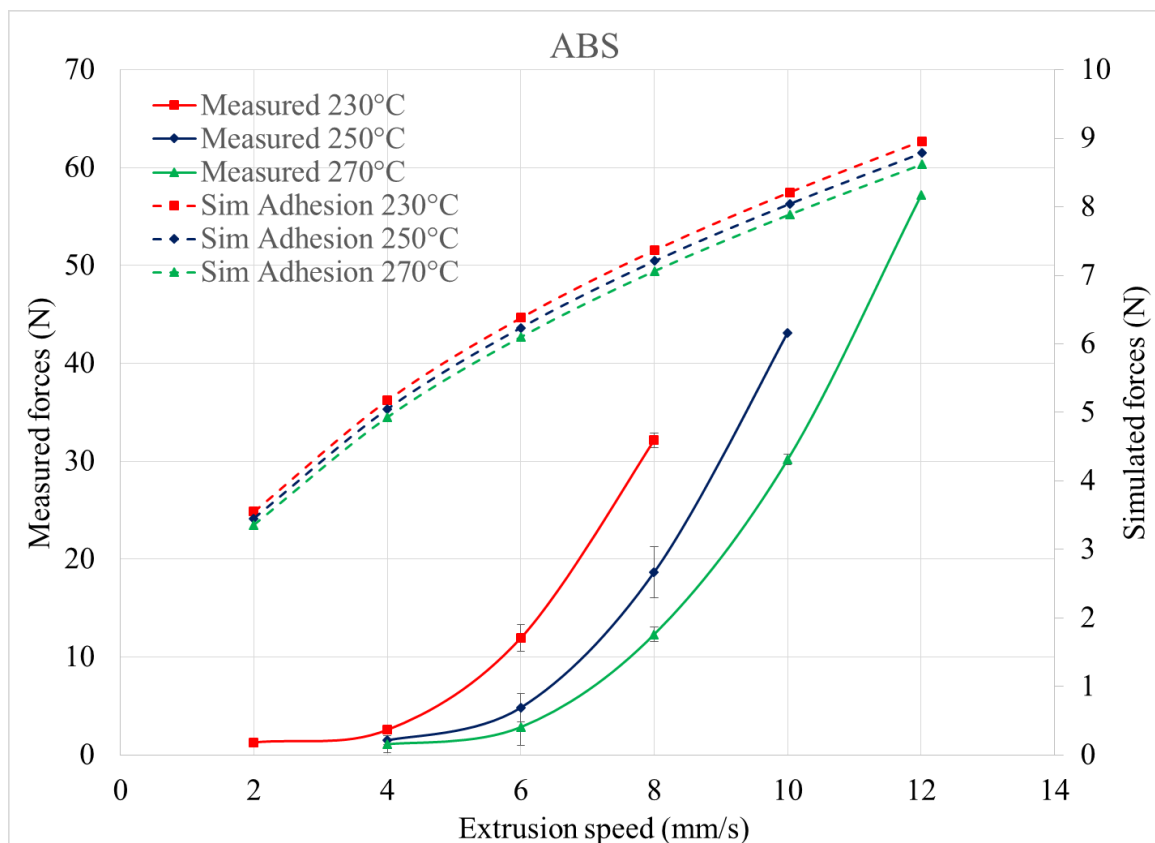


Figure 41 Comparison of simulated and measured extrusion forces for Ultrafuse ABS at different temperatures using wall adhesion (no-slip) boundary condition.

In this configuration Figure 41, a no-slip boundary condition (wall adhesion) was applied to the simulation. The results show an improved match between simulated and measured forces, particularly at 250 °C and 270 °C. This suggests that wall adhesion more accurately represents the real extrusion behavior of Ultrafuse ABS in this context. While the predicted forces are still lower than the experimental values, the deviation is reduced compared to the wall slip case. Despite this improvement, large discrepancies still remain. However, further refinement such as implementing temperature-dependent viscosity or more detailed slip models could enhance the accuracy.

## 9 CONCLUSION

This work investigated the feeding force during extrusion-based additive manufacturing using both experimental measurements and numerical simulation. The focus was placed on understanding how temperature, flow rate, material and wall conditions affect the resistance during filament feeding through a nozzle.

The experimental results showed a consistent trend: increasing feed rates leads to higher extrusion forces, while increasing die temperatures reduces the required force. These trends reflect the expected influence of shear and temperature on viscosity, and confirm the suitability of the test setup for capturing realistic force values.

Simulation efforts were carried out using Ansys Polyflow for ABS material. Although not in perfect agreement with the measured forces, the model captured key trends in the data. Differences between the simulation and experiment can be linked to assumptions in material behavior, unknown parameters at the wall interface, or simplifications in the geometry. These areas offer potential for further investigations and refinements.

For the 316L-polymer composite, numerical simulation was not feasible due to the lack of reliable viscosity data. This highlights a limitation in modeling metal-filled filaments and points to the need for advanced rheological characterization in future works.

Overall, the combined experimental–numerical approach provided a deeper insight into the feeding behavior of thermoplastic filaments. The results can support process optimization, improve material selection, and serve as a foundation for more advanced modeling of extrusion systems.

## 10 REFERENCES

- [1] GARDAN, Julien. Additive manufacturing technologies: state of the art and trends [online]. *International Journal of Production Research*. 2016, **54**(10), 3118-3132. Available from: 10.1080/00207543.2015.1115909.
- [2] BELLINI, Costanzo, Filippo BERTO, Vittorio DI COCCO, Francesco IACOVIELLO, Larisa Patricia MOCANU, and Nima RAZAVI. Additive manufacturing processes for metals and effects of defects on mechanical strength: a review [online]. *Procedia Structural Integrity*. 2021, **33**, 498-508. Available from: 10.1016/j.prostr.2021.10.057.
- [3] COSTABILE, G., M. FERA, F. FRUGGIERO, A. LAMBIASE, and D. PHAM. Cost models of additive manufacturing: A literature review [online]. *International Journal of Industrial Engineering Computations*. 2017, 263-283. Available from: 10.5267/j.ijiec.2016.9.001.
- [4] FORWARD-AM. *Ultrafuse ABS. Extend Technical Datasheet*.
- [5] WOLDERING, Sharon. *Ultrafuse\_316L\_TDS\_EN\_v1.1*.
- [6] ADDITIVE MANUFACTURING RESEARCH GROUP, LOUGHBOROUGH UNIVERSITY. *About Additive Manufacturing* [online]. Available from: [https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialextrusion/#:~:text=Fuse%20deposition%20modelling%20\(FDM\)%20is,then%20deposited%20layer%20by%20layer](https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialextrusion/#:~:text=Fuse%20deposition%20modelling%20(FDM)%20is,then%20deposited%20layer%20by%20layer).
- [7] *Introduction to Material Extrusion - FDM* [viewed 10 February 2025]. Available from: <https://www.3ds.com/make/guide/process/material-extrusion>.
- [8] KUMAR, M. Saravana, Muhammad Umar FAROOQ, Nimel Sworna ROSS, Che-Hua YANG, V. KAVIMANI, and Adeolu A. ADEDIRAN. Achieving effective interlayer bonding of PLA parts during the material extrusion process with enhanced mechanical properties [online]. *Scientific reports*. 2023, **13**(1), 6800. Available from: 10.1038/s41598-023-33510-7.
- [9] SUN, Q., G. M. RIZVI, C. T. BELLEHUMEUR, and P. GU. Effect of processing conditions on the bonding quality of FDM polymer filaments [online]. *Rapid Prototyping Journal*. 2008, **14**(2), 72-80. Available from: 10.1108/13552540810862028.
- [10] N. TURNER, Brian, Robert STRONG, and Scott A. GOLD. A review of melt extrusion additive manufacturing processes: I. Process design and modeling [online]. *Rapid Prototyping Journal*. 2014, **20**(3), 192-204. Available from: 10.1108/RPJ-01-2013-0012.
- [11] BIKAS, H., P. STAVROPOULOS, and G. CHRYSSOLOURIS. Additive manufacturing methods and modelling approaches: a critical review [online]. *The International Journal of Advanced Manufacturing Technology*. 2016, **83**(1-4), 389-405. Available from: 10.1007/s00170-015-7576-2.
- [12] GUIDETTI, Xavier, Nathan MINGARD, Raul CRUZ-OLIVER, Yannick NAGEL, Marvin RUEPPEL, Alisa RUPENYAN, Efe C. BALTA, and John LYGEROS. Force controlled printing for material extrusion additive manufacturing [online]. *Additive Manufacturing*. 2024, **89**, 104297. Available from: 10.1016/j.addma.2024.104297.

- [13] SERDECZNY, Marcin P., Raphaël COMMINAL, David B. PEDERSEN, and Jon SPANGENBERG. Experimental validation of a numerical model for the strand shape in material extrusion additive manufacturing [online]. *Additive Manufacturing*. 2018, **24**, 145-153. Available from: 10.1016/j.addma.2018.09.022.
- [14] SHAQOUR, Bahaa, Mohammad ABUABIAH, Salameh ABDEL-FATTAH, Adel JUAIDI, Ramez ABDALLAH, Waleed ABUZAINA, Mohammad QAROUT, Bart VERLEIJE, and Paul COS. Gaining a better understanding of the extrusion process in fused filament fabrication 3D printing: a review [online]. *The International Journal of Advanced Manufacturing Technology*. 2021, **114**(5-6), 1279-1291. Available from: 10.1007/s00170-021-06918-6.
- [15] NIENHAUS, Vinzenz, Kevin SMITH, Dieter SPIEHL, and Edgar DÖRSAM. Investigations on nozzle geometry in fused filament fabrication [online]. *Additive Manufacturing*. 2019, **28**, 711-718. Available from: 10.1016/j.addma.2019.06.019.
- [16] TURNER, Brian N., Robert STRONG, and Scott A. GOLD. A review of melt extrusion additive manufacturing processes: I. Process design and modeling [online]. *Rapid Prototyping Journal*. 2014, **20**(3), 192-204. Available from: 10.1108/RPJ-01-2013-0012.
- [17] ABRAHAM, Ruben Eapen, Ye HONG, Manjarik MRINAL, and Cheng LUO. Buckling-aided gap filling during the extrusion of Acrylonitrile Butadiene Styrene for additive manufacturing [online]. *Materials Letters*. 2023, **334**, 133710. Available from: 10.1016/j.matlet.2022.133710.
- [18] LEE, Juhyeong, Nikhil A. PATIL, and Jay Hoon PARK. Correlating microstructural and rheological variations in acrylonitrile-butadiene-styrene (ABS) with interlayer bond formation in material extrusion additive manufacturing [online]. *Additive Manufacturing*. 2024, **96**, 104553. Available from: 10.1016/j.addma.2024.104553.
- [19] *Everything you need to know about ABS 3D Printing*. Available from: [https://www.makerbot.com/stories/abs-3d-printing/?utm\\_source=chatgpt.com](https://www.makerbot.com/stories/abs-3d-printing/?utm_source=chatgpt.com).
- [20] XU, Mengjia, Bosheng LIU, Yunqiang ZHAO, Zhenmin WANG, and Zhibo DONG. Direct joining of thermoplastic ABS to aluminium alloy 6061-T6 using friction lap welding [online]. *Science and Technology of Welding and Joining*. 2020, **25**(5), 391-397. Available from: 10.1080/13621718.2020.1719304.
- [21] ENGINEERS EDGE. *ABS Plastic Filament Engineering information* [online]. Available from: [https://www.engineersedge.com/3D\\_Printing/abs\\_plastic\\_filament\\_engineering\\_information\\_14211.htm?utm\\_source=chatgpt.com](https://www.engineersedge.com/3D_Printing/abs_plastic_filament_engineering_information_14211.htm?utm_source=chatgpt.com).
- [22] PROTO LABS. *ABS Plastic: Understand the Key Benefits and Applications* [online]. Available from: <https://www.protolabs.com/materials/abs/#:~:text=Disadvantages%20of%20ABS&text=It%20can%20become%20brittle%20and,burn%2C%20releasing%20potentially%20toxic%20fumes>.
- [23] FORWARD-AM. *Ultrafuse 316L* [online]. Available from: <https://forward-am.com/material-portfolio/ultrafuse-filaments-for-fused-filaments-fabrication-fff/metal-filaments/ultrafuse-316l/#:~:text=Ultrafuse%20is%20designed,to%20ensure%20ease%20of%20handling>.

- [24] WOLDERING, Sharon. Ultrafuse\_316L\_TDS\_EN\_v1.1.
- [25] SARZYŃSKI, Marcin, Paweł PŁATEK, Patryk CEDRO, Urvashi GUNPUTH, Paul WOOD, and Alexis RUSINEK. Mechanical Behavior of 3D-Printed Zig-Zag Honeycomb Structures Made of BASF Ultrafuse 316L [online]. *Materials (Basel, Switzerland)*. 2024, **17**(24). Available from: 10.3390/ma17246194.
- [26] MERKLE, and RALPH. Safety data sheet [online]. 2021. Available from: chrome-extension://efaidnbmnnnibpcajpcgclefindmkaj/https://forward-am.com/wp-content/uploads/2021/04/ULTRAFUSE%C2%AE316L\_11123987\_SDS\_GEN\_EU\_EN\_5-0\_NL07.pdf.
- [27] BASF Ultrafuse 316L - User Guidelines.
- [28] RAISE 3D. *Ultrafuse 316L* [online]. Available from: [https://shop.raise3d.com/products/ultrafuse-316l?srltid=AfmBOor-2bPV-5lbZ\\_cdJoXnFrIu5ClhAi8lQBxVf7YmtygikE29XjKP](https://shop.raise3d.com/products/ultrafuse-316l?srltid=AfmBOor-2bPV-5lbZ_cdJoXnFrIu5ClhAi8lQBxVf7YmtygikE29XjKP).
- [29] KOZŁOWSKI, Ryszard M. and Maria MACKIEWICZ-TALARCZYK. *Testing of natural textile fibres* [online]. 15.6.1 *Differential scanning calorimetry*. Available from: [https://www.sciencedirect.com/topics/materials-science/differential-scanning-calorimetry#:~:text=Differential%20scanning%20calorimetry%20\(DSC\)%20is%20a%20method%20used%20to%20study,relative%20to%20a%20reference%20material](https://www.sciencedirect.com/topics/materials-science/differential-scanning-calorimetry#:~:text=Differential%20scanning%20calorimetry%20(DSC)%20is%20a%20method%20used%20to%20study,relative%20to%20a%20reference%20material).
- [30] PIONTECK, Jürgen. Determination of Pressure Dependence of Polymer Phase Transitions by pvT Analysis [online]. *Polymers*. 2018, **10**(6). Available from: 10.3390/polym10060578.
- [31] LUY, J.-F., G. RGNIER, Ph. LE BOT, D. DELAUNAY, and R. FULCHIRON. pvT measurement methodology for semicrystalline polymers to simulate injection-molding process [online]. *Journal of Applied Polymer Science*. 2001, **79**(2), 302-311. Available from: 10.1002/1097-4628(20010110)79:2<302::AID-APP120>3.0.CO;2-I.
- [32] S. M. MARCUS AND R. L. BLAINE. thermal conductivity of polymers, glasses & ceramics by MDSC, TA-086.
- [33] DO, Nu Bich Duyen, Kristin IMENES, Knut E. AASMUNDTVEIT, Hoang-Vu NGUYEN, and Erik ANDREASSEN. Thermal Conductivity and Mechanical Properties of Polymer Composites with Hexagonal Boron Nitride-A Comparison of Three Processing Methods: Injection Moulding, Powder Bed Fusion and Casting [online]. *Polymers*. 2023, **15**(6). Available from: 10.3390/polym15061552.
- [34] CHEN, Shaoyong, Mingyue LIU, Huiming HUANG, Lan CHENG, and Hong-Ping ZHAO. Mechanical properties of Bombyx mori silkworm silk fibre and its corresponding silk fibroin filament: A comparative study [online]. *Materials & Design*. 2019, **181**, 108077. Available from: 10.1016/j.matdes.2019.108077.
- [35] NORDIN, Ahmad Amri, Siti Nazehah Mohd SOFIAN, Sharifah Imihezri Syed SHAHARUDDIN, Norhashimah SHAFFIAR, Abd Malek Abdul HAMID, and Nor Aiman SUKINDAR. A Comparison of the Thermal Conductivity of 3D Printed ABS and ABS/Graphite at Various Infill Patterns and Densities. In: Md. Abdul Maleque, Ahmad Zahirani Ahmad Azhar, Norshahida Sarifuddin, Sharifah Imihezri Syed Shaharuddin, Afifah Mohd Ali, and Nor Farah Huda Abdul Halim, eds. *Proceeding of 5th International Conference on Advances in Manufacturing and Materials Engineering*. Singapore: Springer Nature Singapore, 2023, pp. 429-435.

- [36] STEEL PRO GROUP. *Thermal Conductivity of Stainless Steel Explained & Chart* [online]. Available from: <https://steelprogroup.com/stainless-steel/properties/thermal-conductivity/>.
- [37] SCIENCEDIRECT. *Handbook of Natural Fibres* [online]. 20 February 2025, 12:00 [viewed 20 February 2025]. Available from: <https://www.sciencedirect.com/book/9780128183984/handbook-of-natural-fibres>.
- [38] ALEXANDER YA, Malkin, ed. *Rheology: Concepts, Methods, and Applications*, 2012. 978-1-895198-49-2.
- [39] BARNES, Howard A. *A handbook of elementary rheology*. Aberystwyth: University of Wales Institute of Non-Newtonian Fluid Mechanics, 2000. 0953803201.
- [40] IM, Jaegyun, Min CHAN KIM, Chanwoo PARK, Yun Ho JEONG, Beomjin JEONG, Kyu HYUN, and Jaegun LEE. Investigation into shear-thinning behavior in wet spinning of carbon nanotube fibers modeled by power law viscosity model [online]. *Carbon*. 2025, **232**, 119766. Available from: 10.1016/j.carbon.2024.119766.
- [41] KHODADADI, Amin, Gholamhossein LIAGHAT, Alireza TAHERZADEH-FARD, and Davoud SHAHGHOLIAN-GHAHFAROKHI. Impact characteristics of soft composites using shear thickening fluid and natural rubber—A review of current status [online]. *Composite Structures*. 2021, **271**, 114092. Available from: 10.1016/j.compstruct.2021.114092.
- [42] THOMAS, and MEZGER, eds. *The Rheology Handbook*. 5th ed. Hannover, Germany: European Coatings, 2020. 9783866305328/9783866305366.
- [43] NETZSCH. *Bagley Correction* [online]. Available from: <https://analyzing-testing.netzsch.com/en/know-how/glossary/bagley-correction>.
- [44] NETZSCH. *Rabinowitsch Correction* [online]. Available from: <https://analyzing-testing.netzsch.com/en/know-how/glossary/rabinowitsch-correction>.
- [45] HAUSWIRTH, Scott C., Christopher A. BOWERS, Christopher P. FOWLER, Pamela B. SCHULTZ, Amanda Dye HAUSWIRTH, Timothy WEIGAND, and Cass T. MILLER. Modeling cross model non-Newtonian fluid flow in porous media [online]. *Journal of contaminant hydrology*. 2020, **235**, 103708. Available from: 10.1016/j.jconhyd.2020.103708.
- [46] H. A. BARNES, J. F. HUTTON, AND K. WALTERS. Polyflow User's Guide.
- [47] ERICO MALTINI, and MONICA ANESE. Evaluation of viscosities of amorphous phases in partially frozen systems by WLF kinetics and glass transition temperatures [online]. Available from: 10.1016/0963-9969(95)00006-8.
- [48] KIRAN, Abhilash, Josef HODEK, Jaroslav VAVŘÍK, Miroslav URBÁNEK, and Jan DŽUGAN. Numerical Simulation Development and Computational Optimization for Directed Energy Deposition Additive Manufacturing Process [online]. *Materials (Basel, Switzerland)*. 2020, **13**(11). Available from: 10.3390/ma13112666.
- [49] BALTA, Efe C., and Atakan ALTINKAYNAK. Numerical and experimental analysis of bead cross-sectional geometry in fused filament fabrication [online]. *Rapid Prototyping Journal*. 2022, **28**(10), 1882-1894. Available from: 10.1108/RPJ-09-2021-0255.

- [50] JĄSKOWIEC, Jan, and Piotr PLUCIŃSKI. Orthogonalization in high-order finite element method [online]. *Computers & Structures*. 2025, **311**, 107692. Available from: 10.1016/j.compstruc.2025.107692.
- [51] RHEOSENSE. *Rheology model fitting and corrections* [online]. Available from: <https://blog.rheosense.com/rheology-model-fitting-and-corrections>.
- [52] SCHULLER, Tomás, Maziyar JALAAL, Paola FANZIO, and Francisco J. GALINDO-ROSALES. Optimal shape design of printing nozzles for extrusion-based additive manufacturing [online]. *Additive Manufacturing*. 2024, **84**, 104130. Available from: 10.1016/j.addma.2024.104130.
- [53] COMMINAL, Raphaël, and Marcin P. SERDECZNY. Numerical simulation of extrusion-based additive manufacturing - Effect of the nozzle geometry on the strand cross-section. 2018.
- [54] SHAUKHAROVA, Azhar, Yi LIANG, Hutian FENG, and Bin XU. Study of Stiffness of Linear Guide Pairs by Experiment and FEA [online]. *World Journal of Engineering and Technology*. 2016, **04**(03), 115-128. Available from: 10.4236/wjet.2016.43D015.
- [55] E3D-ONLINE. Technical Drawings [online]. E3D-v6 3mm Direct with Sensor Cartridge. 2016. Available from: <chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.th3dstudio.com/wp-content/uploads/2022/07/V6Datasheet-2019.pdf?srsltid=AfmBOorJi4qHm5AxMYef0DuSzFnYpIKesc2IEk8MR7GeI4Oh34W0Pr4U>.
- [56] *VDI-Wärmeatlas. Mit 320 Tabellen*. 11., bearb. und erw. Aufl. Berlin, Heidelberg: Springer Vieweg, 2013. VDI/-Buch]. 3642199828.

## LIST OF FIGURES

|                                                                                                                                                                                                                                  |    |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| FIGURE 1 OUTLINE OF THE MEX PROCESS'S [8] .....                                                                                                                                                                                  | 15 |
| FIGURE 2 EXTRUSION FORCE VS FILAMENT FEED VELOCITY AT DIFFERENT TEMPERATURES<br>[15] .....                                                                                                                                       | 17 |
| FIGURE 3 FILAMENT BUCKLING AT LIQUEFIER ENTRANCE [16] .....                                                                                                                                                                      | 17 |
| FIGURE 4 VISUAL SEQUENCE OF FILAMENT BUCKLING AND GAP FILLING WITHIN THE<br>OBSERVATION TUBE [17] .....                                                                                                                          | 18 |
| FIGURE 5 CHEMICAL STRUCTURE OF ABS [20] .....                                                                                                                                                                                    | 19 |
| FIGURE 6 DSC CURVE ILLUSTRATING THERMAL TRANSITIONS [29] .....                                                                                                                                                                   | 23 |
| FIGURE 7 METTLER TOLEDO DSC 1 STARE SYSTEM .....                                                                                                                                                                                 | 24 |
| FIGURE 8 AN ILLUSTRATION OF A pVT CELL [31] .....                                                                                                                                                                                | 25 |
| FIGURE 9 GÖTTFERT RG 50 SYSTEM .....                                                                                                                                                                                             | 26 |
| FIGURE 10 VISCOSITY BEHAVIOR OF NEWTONIAN AND NON-NEWTONIAN FLUIDS [38] .....                                                                                                                                                    | 28 |
| FIGURE 11 BAGLEY CORRECTION [43] .....                                                                                                                                                                                           | 30 |
| FIGURE 12 POWER-LAW MODEL [45] .....                                                                                                                                                                                             | 31 |
| FIGURE 13 CROSS MODEL [45] .....                                                                                                                                                                                                 | 32 |
| FIGURE 14 FILAMENT FORCE MEASUREMENT DEVELOPED FOR EXTRUSION SETUP .....                                                                                                                                                         | 34 |
| FIGURE 15 EXTRUSION FORCE TEST SET-UP .....                                                                                                                                                                                      | 35 |
| FIGURE 16 FEM FLOW DIAGRAM [54] .....                                                                                                                                                                                            | 39 |
| FIGURE 17 NOZZLE GEOMETRY [55] .....                                                                                                                                                                                             | 40 |
| FIGURE 18 SIMULATION MODEL CONSTRUCTION INTO ANSYS .....                                                                                                                                                                         | 40 |
| FIGURE 19 INDIVIDUAL PARTS FOR E3D DIE: A) HEAT SOURCE, B) NOZZLE, C) MELT, D) HEAT<br>BREAK, .....                                                                                                                              | 41 |
| FIGURE 20 3D VIEW OF THE OVERALL MESH AND NOZZLE REGION .....                                                                                                                                                                    | 42 |
| FIGURE 21 DEFINITION OF SLIP BOUNDARY CONDITIONS AND DIE REGION SELECTION IN<br>ANSYS POLYFLOW .....                                                                                                                             | 43 |
| FIGURE 22 DSC (HEAT CAPACITY MEASUREMENT OF ULTRAFUSE ABS AND ULTRAFUSE<br>316L) .....                                                                                                                                           | 47 |
| FIGURE 23 pVT OF ULTRAFUSE ABS .....                                                                                                                                                                                             | 48 |
| FIGURE 24 pVT OF ULTRAFUSE 316L .....                                                                                                                                                                                            | 48 |
| FIGURE 25 TEMPERATURE OVER TIME CURVES OF ULTRAFUSE ABS AND ULTRAFUSE 316L .....                                                                                                                                                 | 49 |
| FIGURE 26 VISCOSITY OF ABS AT MEASURED TEMPERATURES .....                                                                                                                                                                        | 50 |
| FIGURE 27 TEMPERATURE SHIFT OF ABS .....                                                                                                                                                                                         | 51 |
| FIGURE 28 MEASURED VISCOSITY CURVES OF ULTRAFUSE 316L .....                                                                                                                                                                      | 52 |
| FIGURE 29 FORCE GRAPHS FOR ABS AND 316L .....                                                                                                                                                                                    | 54 |
| FIGURE 30 TEMPERATURE DISTRIBUTION AT DIFFERENT FILAMENT FEEDING VELOCITIES FOR<br>230 °C. THE TOP IMAGE CORRESPONDS TO THE LOWEST VELOCITY (2 MM/S), WHILE THE<br>BOTTOM IMAGE REPRESENTS THE HIGHEST VELOCITY (12 MM/S). ..... | 56 |
| FIGURE 31 TEMPERATURE DISTRIBUTION ALONG THE DIE AT 230 °C FOR DIFFERENT FEED<br>RATES .....                                                                                                                                     | 57 |
| FIGURE 32 TEMPERATURE DISTRIBUTION WITH DIFFERENT FILAMENT FEEDING FOR 270 °C.<br>THE TOP CORRESPONDS TO THE LOWEST VELOCITY (2 MM/S), WHILE THE BOTTOM IMAGE<br>REPRESENTS THE HIGHEST VELOCITY (12 MM/S). .....                | 58 |
| FIGURE 33 TEMPERATURE PROFILES ALONG THE FLOW DIRECTION AT 270 °C FOR VARYING<br>FEED RATES .....                                                                                                                                | 59 |
| FIGURE 34 VELOCITY DISTRIBUTION IN THE EXTRUSION HEAD AT 270 °C. LEFT 2 MM/S AND<br>RIGHT 12 MM/S .....                                                                                                                          | 60 |
| FIGURE 35 VELOCITY PROFILES IN THE MIDDLE (TOP) AND AT THE WALL (BOTTOM) OF THE<br>PTFE TUBE AT 270 °C FOR VARIOUS FILAMENT FEEDING SPEEDS. ....                                                                                 | 61 |

|                                                                                                                                                                          |    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| FIGURE 36 TEMPERATURE DISTRIBUTION AT 270 °C FOR SIMULATION WITH WALL ADHESION<br>(LEFT: 2 MM/S, RIGHT: 12 MM/S). .....                                                  | 63 |
| FIGURE 37 VELOCITY DISTRIBUTION IN THE EXTRUSION HEAD AT 270 °C WITH WALL<br>ADHESION, LEFT 2 MM/S RIGHT 12 MM/S .....                                                   | 64 |
| FIGURE 38 VELOCITY PROFILES AT 270 °C IN THE NOZZLE CENTER WITH WALL ADHESION ..                                                                                         | 64 |
| FIGURE 39 TEMPERATURE PROFILES AT 270 °C COMPARING WALL ADHESION AND WALL SLIP.<br>.....                                                                                 | 65 |
| FIGURE 40 COMPARISON OF SIMULATED AND MEASURED EXTRUSION FORCES FOR<br>ULTRAFUSE ABS AT DIFFERENT TEMPERATURES USING WALL SLIP BOUNDARY<br>CONDITION. ....               | 66 |
| FIGURE 41 COMPARISON OF SIMULATED AND MEASURED EXTRUSION FORCES FOR<br>ULTRAFUSE ABS AT DIFFERENT TEMPERATURES USING WALL ADHESION (NO-SLIP)<br>BOUNDARY CONDITION. .... | 67 |

## LIST OF TABLES

|                                                                                                                            |    |
|----------------------------------------------------------------------------------------------------------------------------|----|
| TABLE 1 DRYING RECOMMENDATIONS ABS FILAMENT [4].....                                                                       | 20 |
| TABLE 2 GENERAL PROPERTIES OF ABS FILAMENT [4].....                                                                        | 20 |
| TABLE 3 FLEXURAL AND TENSILE PROPERTIES OF ABS FILAMENT [4] .....                                                          | 20 |
| TABLE 4 MASS LOSS AND DIMENSIONAL SHRINKAGE OF ALL STRUCTURE TYPES AFTER<br>DEBINDING AND SINTERING [25]. .....            | 21 |
| TABLE 5 MEASUREMENT PARAMETERS FOR ABS AND 316L .....                                                                      | 26 |
| TABLE 6 THERMAL CONDUCTIVITY MEASUREMENT PARAMETERS FOR ABS AND 316L.....                                                  | 28 |
| TABLE 7 PARAMETERS FOR VISCOSITY MEASUREMENT OF ULTRAFUSE ABS AND ULTRAFUSE<br>316L .....                                  | 34 |
| TABLE 8 EXTRUSION TEST PARAMETERS .....                                                                                    | 35 |
| TABLE 9 THERMAL PROPERTIES OF MATERIALS [56] .....                                                                         | 42 |
| TABLE 10 VISCOSITY MODEL FOR POLYFLOW OF THE ABS MELT .....                                                                | 44 |
| TABLE 11 MATERIAL DATA FOR POLYFLOW OF THE ABS MELT .....                                                                  | 44 |
| TABLE 12 MATERIAL DATA FOR POLYFLOW OF THE THE SOLID PARTS [56] .....                                                      | 45 |
| TABLE 13 MEASURED THERMAL CONDUCTIVITY ( $\Lambda$ ) OF ULTRAFUSE ABS AND ULTRAFUSE<br>316L AT SELECTED TEMPERATURES. .... | 49 |
| TABLE 14 PARAMETERS FOR ABS .....                                                                                          | 51 |

## LIST OF ABBREVIATIONS

|                                                             |                                                           |
|-------------------------------------------------------------|-----------------------------------------------------------|
| CAD - Computer-Aided Design                                 | $\eta$ - Viscosity (Pa·s)                                 |
| AM - Additive Manufacturing                                 | $K$ - Consistency index (Pa·s <sup>n</sup> )              |
| 3D - Three-Dimensional                                      | $\tau$ - Shear stress (Pa)                                |
| FDM <sup>TM</sup> - Fused Deposition Modeling <sup>TM</sup> | $\rho$ - Density (kg/m <sup>3</sup> )                     |
| FFF - Fused Filament Fabrication                            | $v$ - Velocity field (m/s)                                |
| MEX - Material Extrusion                                    | $p$ - Pressure (Pa)                                       |
| CFD - Computational Fluid Dynamics                          | $F$ - External force                                      |
| DSC - Differential Scanning Calorimetry                     | $\eta_0$ - Zero shear viscosity (Pa·s)                    |
| ABS - Acrylonitrile Butadiene Styrene                       | $\eta_\infty$ - Infinite shear viscosity (Pa·s)           |
| PLA - Polylactic Acid                                       | $\lambda$ - Time constant (s)                             |
| HIPS - High-Impact Polystyrene                              | $m$ - Shear-thinning exponent                             |
| TPU - Thermoplastic Polyurethane                            | $a$ - Material constant (dimensionless)                   |
| PA - Polyamides                                             | $T$ - Temperature (K)                                     |
| PEEK - Polyether Ether Ketone                               | $T_0$ - Reference temperature (K)                         |
| PEI - Polyetherimide                                        | $T_g$ - Glass transition temperature (K)                  |
| WLF - Williams-Landel-Ferry                                 | $T_a$ - Activation temperature (K)                        |
| POM - Polyoxymethylene                                      | $C_1$ - WLF constant (dimensionless)                      |
| UV - Ultraviolet                                            | $C_2$ - WLF constant (K)                                  |
| BASF - Badische Anilin- und Soda-Fabrik                     | $q$ - Heat energy (J)                                     |
| pVT - Pressure-Volume-Temperature                           | $t$ - Time (s)                                            |
| PTFE - Polytetrafluoroethylene                              | $\Delta T$ - Temperature change (K)                       |
| HPCR - High-Pressure Capillary Rheometer                    | $C_p$ - Heat capacity (J/K)                               |
| $\lambda$ - Thermal conductivity (W/m·K)                    | $\dot{\gamma}$ - Shear rate (s <sup>-1</sup> )            |
| $\alpha$ - activation energy (J·mol <sup>-1</sup> )         | $\dot{\gamma}_a$ - Apparent shear rate (s <sup>-1</sup> ) |
| $n$ - Flow behavior index                                   |                                                           |